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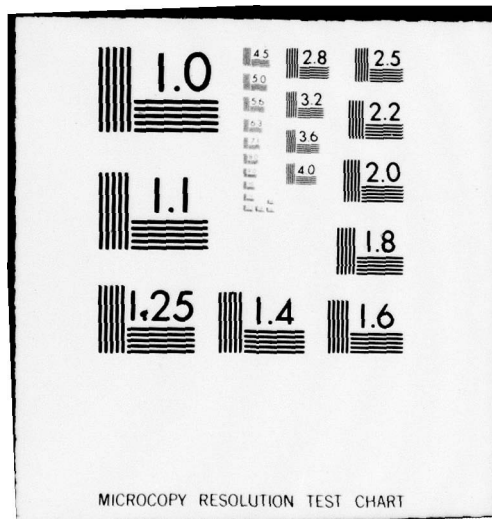
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**DAVID W. TAYLOR NAVAL SHIP
RESEARCH AND DEVELOPMENT CENTER**

Bethesda, Maryland 20084



**ACCURACY OF HYDROFOIL LOADING PREDICTIONS OBTAINED
FROM A LIFTING-SURFACE COMPUTER PROGRAM**

by

Peter K. Besch
Edwin P. Rood, Jr.



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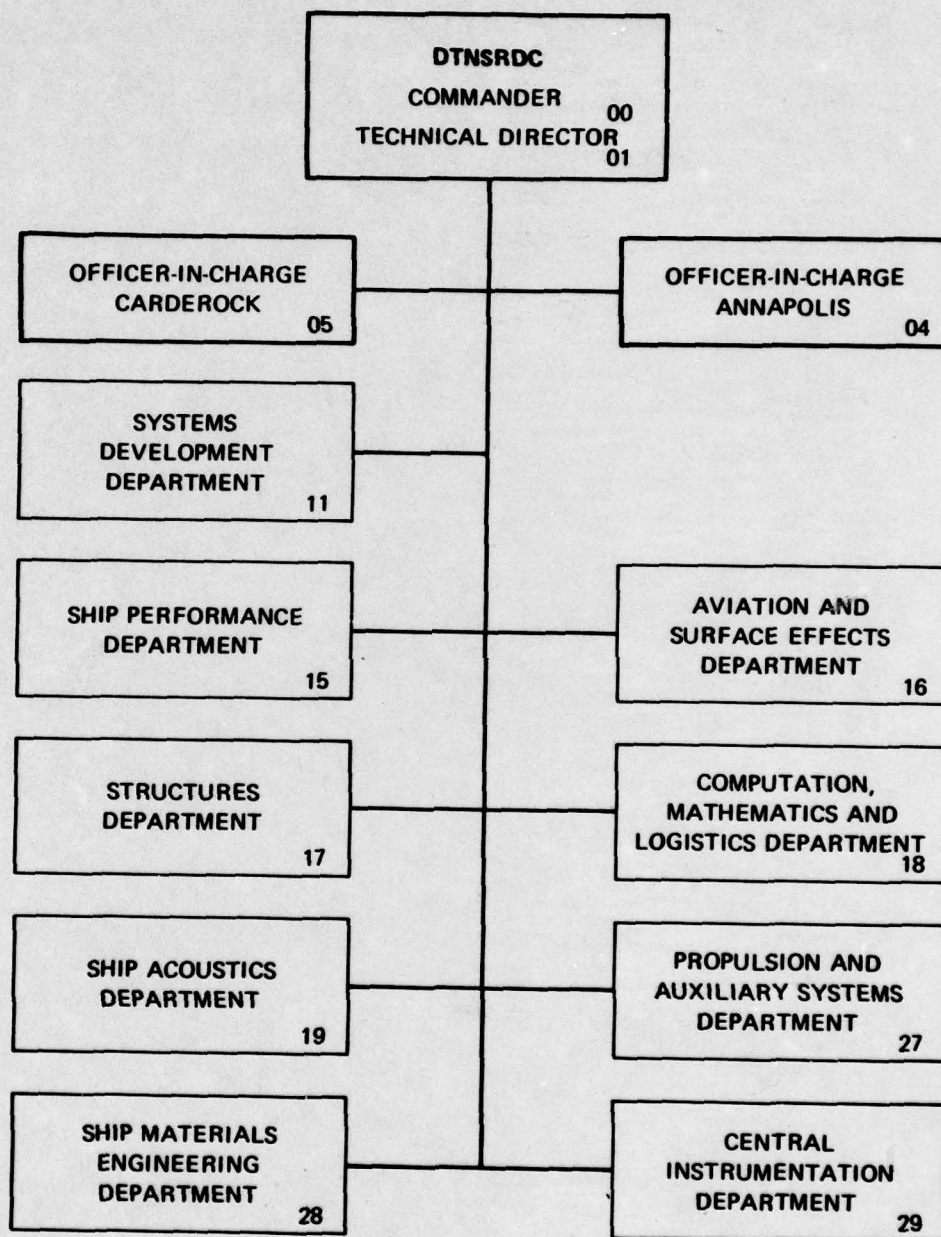
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→ accurate. Determination of the accuracy was hindered by insufficient or imprecise data. Documentation for the computer program is given. ↗

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NOTATION

| | |
|----------------------------|---|
| A | Integration surface equivalent to foil surface |
| AR | Aspect ratio; b^2/S |
| a | Refers to an airfoil or hydrofoil mean line producing a uniform load distribution forward of a and a distribution decreasing linearly to zero aft of a; a is given in fraction of chord |
| a_{nm} | Coefficient of series representing pressure jump Δp |
| b | Span of submerged foil section, measured perpendicular to free stream |
| b' | Fractional distance along submerged foil section, measured perpendicular to free stream |
| C_L | Lift coefficient; increases with increasing angle of attack; lift/qS |
| $C_{L\alpha}, C_{L\delta}$ | Rate of change of C_L or C_L with respect to angle of attack α or δ , respectively, in units of radians ⁻¹ unless otherwise noted |
| C_ℓ, C_l | Local lift coefficient; (lift per unit span)/qc |
| C_M | Pitching moment coefficient; positive tending to increase angle of attack; (pitching moment)/qSc' |
| $C_{M\alpha}, C_{M\delta}$ | Rate of change of C_M with respect to angle of attack α or δ , respectively, in units of radians ⁻¹ |
| C_m | Local pitching moment coefficient; (pitching moment per unit span)/qSc' |
| C_R | Roll moment coefficient; (roll moment)/qSc' |
| c | Chord length of lifting surface, measured in streamwise direction |
| c' | Mean geometric chord; S/b |
| c_o | Root chord of section (chord at $b' = 0$) |
| f | Location of foil surface |

| | |
|-----------|--|
| f_i | i^{th} spanwise pressure mode |
| h | Depth beneath undisturbed free surface |
| j | Number of chordwise control points |
| K | Kernel function |
| k | Reduced frequency, $\omega c'/2U$; also, number of spanwise control points |
| M | Mach number |
| q | Stagnation pressure; $\rho U^2/2$ |
| S | Submerged foil area |
| t | Time |
| U | Free stream velocity |
| U' | Magnitude of orbital velocity due to waves |
| v_n | Downwash, or perturbation velocity induced normal to the undisturbed flow by the foil, positive in direction opposite to direction of positive lift |
| x | Frame of reference coordinate parallel to flow and positive in the same direction as the free stream velocity |
| x_{cp} | Unsteady center of pressure; ratio of magnitude of unsteady moment in phase with lift to the unsteady lift magnitude, expressed as percent of chord aft of the foil leading edge |
| y | Spanwise position or frame of reference coordinate |
| z | Frame of reference coordinate |
| α | Angle of attack relative to flow |
| β | Angular position in flapping motion |
| δ | Unsteady linear displacement of lifting surface from its mean position, normal to surface at zero angle of attack; also, angle of attack of hydrofoil relative to pod |
| ζ | Dummy integration coordinate used for integration over z |
| ζ_w | Wave height from trough to crest |
| η | Dummy integration coordinate used for integration over y |

| | |
|-----------|--|
| θ | Dummy integration coordinate used for chordwise integration |
| Λ | Sweep angle of quarter-chord line |
| λ | Wavelength |
| ξ | Dummy integration coordinate used for integration over x |
| ρ | Fluid mass density |
| τ | Taper ratio; ratio of tip chord to root chord |
| ϕ | Phase angle of loading relative to displacement |
| ω | Circular frequency of oscillation in rad/sec |
| ω' | Circular frequency of wave in fixed coordinate system in rad/sec |

Subscripts

| | |
|------|---|
| o | Single amplitude of subscripted quantity |
| T | Single amplitude at tip of foil |
| w | Single amplitude of effective unsteady angle of attack due to waves |
| 91.7 | Single amplitude at 91.7 percent of foil semispan |

Superscript

| | |
|-----------------------|---------------------------------|
| $(\bar{})$ | Mean value with respect to time |
|-----------------------|---------------------------------|

ABSTRACT

To provide guidance for hydrofoil designers, an extensive operational evaluation was made of a computer-based lifting-surface theory for calculating hydrodynamic loading on hydrofoils in steady and unsteady motion in inviscid, subcavitating flow at finite depth. Both the numerical stability and the accuracy in comparison with model data were estimated. By use of an empirical correction, lift predictions can be made with an accuracy of about 15 to 20 percent, while pitching moment predictions are substantially less accurate. Determination of the accuracy was hindered by insufficient or imprecise data. Documentation for the computer program is given.

ADMINISTRATIVE INFORMATION

This work was authorized and partially funded under the Hydrofoil Development Program of the Naval Sea Systems Command, Subproject S4606, Task 1703, and performed under Work Unit 1153-003. The work was subsequently expanded under the authority of the Naval Material Command (NAVMAT 087), Program Element 62543N, Task Area ZF-43-421-01, and administered by the Ship Performance Department High Performance Vehicles Program (1507) under Work Unit 1500-102.

INTRODUCTION

This report is an evaluation of one version of a commonly-used general approach (lifting-surface theory) to calculating fluid-dynamic loading on airfoils and hydrofoils. This particular treatment was developed by Ashley et al.^{1*} and Widnall² and programmed for computer use by Widnall. The program will be referred to as the Widnall program after its author. The theory is capable of calculating both steady and unsteady loading on nonplanar hydrofoil systems at finite depth. It extends the theory developed by Watkins et al.³ to include nonplanar surfaces, finite depth effects, and cavitation.

The Navy's interest in this type of calculation arises from possible design applications for hydrofoil craft and ship appendages. These applications include certain hydrodynamic performance characteristics (lift and

*A complete listing of references is given on page 183.

side force, for example, but not drag) and, in combination with appropriate structural analyses, predictions of hydroelastic stability of lifting-surface structures.

To establish the usefulness of a calculation for design work, the accuracy of the method must be known. Although the Widnall program has been available for some time, a detailed analysis of its accuracy had not been performed. Therefore, the present study was undertaken. The approach consisted of comparing the program predictions with a large body of available model loading data from both fully-submerged hydrofoils and airfoils. As a part of the effort, the numerical behavior of the calculation was explored to find the most favorable range of numerical parameter values for program operation.

Some relatively limited evaluations of the theory have previously been made. In the initial development,¹ a two-dimensional version was found to agree with analytical results at infinite depth. Subsequently, Pattison⁴ compared the two-dimensional calculation with experimental measurements. Significant differences were found, but some of the discrepancy may have been due to the experimental configuration and measurement uncertainty.

In an evaluation of three-dimensional loading predictions, Langan and Wang⁵ compared results from the Widnall program with experimental loading on several airfoils. Their work was particularly valuable in that it studied fourteen other computer-based calculations as well. Some aspects of both numerical behavior and calculation accuracy relative to experiment were compared. None of the fifteen calculations was numerically stable to three significant figures. Accuracies were usually within 5 percent of airfoil loading data, but the Widnall prediction of lift due to camber was somewhat less accurate (within 9 percent). These latter calculations corresponded to conditions of optimum numerical stability as determined by the present study, part of which preceded that of Langan and Wang.

These results suggest that a program that is more accurate than the Widnall program can be chosen from the above study. However, the capabilities of treating free-surface effects, including surface-piercing configurations, and unsteady loading, not generally available in the other

programs, make the Widnall program potentially more useful in designing hydrofoils. Therefore, the present study is made available to provide a more comprehensive evaluation of the Widnall program by relating its predictions to available hydrofoil and airfoil data.

Both a description of the numerical characteristics, and comparisons between predicted loading and experimental results for the Widnall three-dimensional calculation, are presented in this report. Comparisons are made for both steady and unsteady loading on planar, fully-wetted foils. A description of the program as used, and instructions for program use, are given in the appendices.

The results contained in this report were obtained from a computer program which was a modification of the original version received by the Center. Changes in coding were made by the authors to modify input and output, to increase the number of chordwise integration modes, and to adapt the program to various computers. Results generated by the present program agree with previously published results¹ for equivalent inputs. It is, therefore, believed that the present results are the same as would have been obtained from the original version.

SUMMARY OF THE LIFTING-SURFACE THEORY

The computer programs described in this report are used to compute hydrodynamic loading on three-dimensional hydrofoils in inviscid, sub-cavitating flow² according to the lifting-surface theory presented by Ashley et al.¹ Calculations for hydrofoils in supercavitating flow are not included. A brief summary of the theory will be given in order to facilitate description of program characteristics.

The lifting surface under consideration consists of a foil or combination of foils which may be nonplanar. The surface is assumed to be of zero thickness and to make small angles with the direction of flow. An example of a single nonplanar foil is shown in Figure 1 along with a possible coordinate system. The choice of a coordinate system is limited only by the requirements that flow be in the positive x-direction and that a free surface, when present, coincide with the plane $z = 0$.

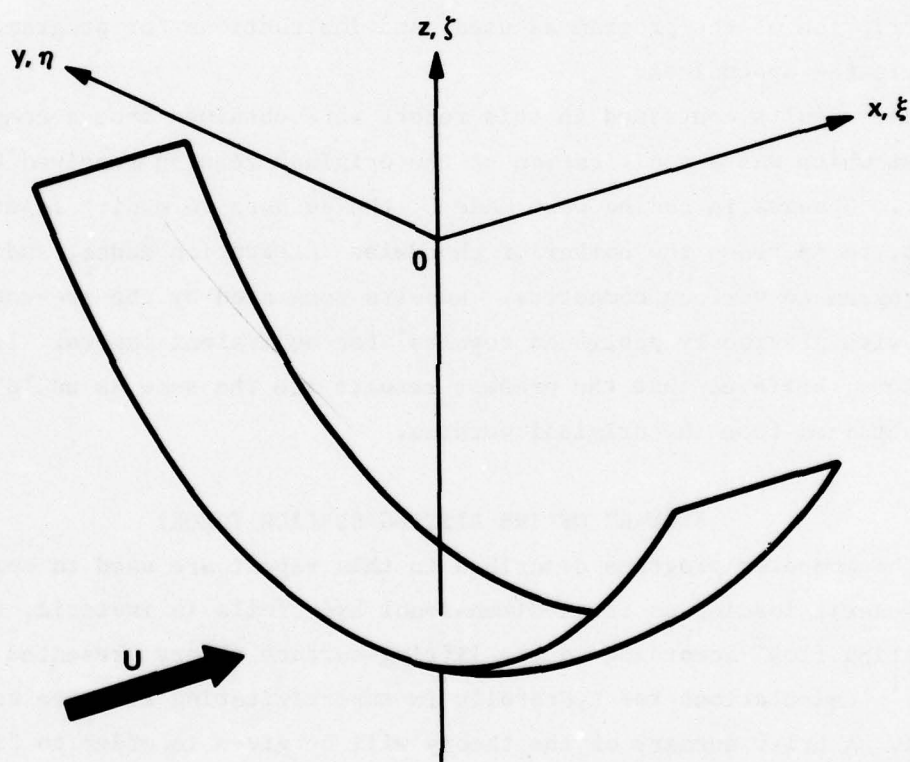


Figure 1 - Configuration of a Nonplanar Lifting Surface

The foil is represented theoretically by a distribution of pressure doublets over the surface of the foil. The downwash, or velocity perturbation normal to the undisturbed flow, is a known quantity determined by flow tangency on the foil and is given by

$$v_n(x, y, z, t) = \iint_A \Delta p(\xi, \eta, \zeta) K(x - \xi, y - \eta, z - \zeta, t) dA \quad (1)$$

The kernel function K is a geometrically determined pressure influence function relating the pressure jump at (ξ, η, ζ) to the velocity induced at (x, y, z) . Time dependence is included as simple harmonic variation in the magnitudes of K and v_n , using complex number notation. Therefore, unsteady loading may be calculated only for sinusoidally varying flow conditions or foil motions. Superposition of Fourier components may be used to treat nonsinusoidal time dependence. The kernel function contains a term for the foil being treated and a term for an image foil equidistant from the free surface when a free surface is present. This representation of a free surface corresponds to assuming that gravity waves created by the foil are unimportant, i.e., infinite Froude number.

The pressure jump distribution, Δp , is found by inverting Equation (1) to give Δp as a function of known quantities. First, Δp is written in the form of a series of chordwise and spanwise pressure modes with unknown coefficients as follows:

$$\begin{aligned} \Delta p(\theta, s') = 8\pi\rho U^2 \frac{b}{c(b')} & \left[\sum_{m=0}^{m'} a_{om} f_m(b') \cot \frac{\theta}{2} \right. \\ & \left. + \sum_{n=1}^{n'} \sum_{m=0}^{m'} \frac{4}{2^{2n}} a_{nm} f_m(b') \sin n\theta \right] \quad (2) \end{aligned}$$

The chordwise modes (the trigonometric functions of θ) used in this expansion were taken from two-dimensional airfoil theory, while the spanwise

modes f_m are left to be specified by the program user according to boundary conditions as described in Appendix B.

The integration indicated in Equation (1) is performed numerically in terms of the unknown pressure mode coefficients a_{nm} . A set of linear equations is obtained relating the pressure mode coefficients to the downwash at a number of locations on the foil. The set of equations is inverted to give the pressure mode coefficients in terms of the downwash values. Finally, the pressure jump distribution and, therefore, any foil loading coefficient may be determined by inserting the foil's downwash values into the inverted equations.

Downwash values are chosen to correspond to flow conditions on the foil. In order to achieve flow tangency, the steady downwash is chosen to be proportional to the local angle of attack. The unsteady downwash consists of flow components needed to maintain the flow in contact with, and tangent to, the foil surface. Calculation of the downwash is described in Appendix B.

For numerical reasons, the downwash must be specified at a minimum number of points on the foil corresponding to the product of the numbers of spanwise and chordwise modes. However, the downwash may be specified at additional points to obtain presumably more accurate results by means of a least square fit inversion technique. Over-specification of downwash values is, in fact, essential to obtaining numerical stability, as described in the following section dealing with numerical behavior.

Final specification of the pressure jump distribution on the foil in terms of the pressure mode coefficients a_{nm} is obtained by combining the downwash input with the coefficient matrix obtained by integration and inversion of Equation (1). Real and imaginary parts of the calculation are treated separately in order to obtain the phase relationship between pressure distribution and displacement.

Load coefficients over various regions of the foil are calculated by expressing the desired coefficient in terms of the pressure jump Δp and integrating over the region. Real and imaginary parts of the integration are treated identically. The present form of the computer program calculates spanwise lift, pitch moment, and roll moment coefficients, chordwise

pressure coefficient distribution for steady loading, total lift, pitch moment and roll moment coefficients, and centers of pressure. Unsteady load coefficients are given in the form of magnitude and phase angle by which the load coefficient leads the unsteady displacement vector. Other load coefficients may be programmed as desired.

The numerical solution procedure just described is controlled by the program user, who specifies the number of collocation stations at which downwash is input, the number of integration intervals, and the number of modes used in the pressure representation. Instructions for generating the program input data are given in Appendix B.

NUMERICAL STABILITY OF THE CALCULATION

In order to discuss the numerical behavior of the program, the computer code names of the numerical variables with their numerical significance will be introduced at this time. A more complete description of the variables is given in Table B.5.

NOLT -- Number of chordwise pressure modes (n in Equation (2))

NOST -- Number of spanwise pressure modes (m in Equation (2))

NOCF -- Number of collocation stations

NCP, MP -- Numbers of chordwise integration steps

NI -- Number of spanwise integration steps

The Widnall program was exercised with a wide range of values for the above quantities. The object was to find a combination of parameter values which produced a numerically stable calculation. The term numerical stability is used to indicate a condition in which several significant figures in the calculated quantities do not change when the input quantities are varied by a small amount.

Four hydrofoil configurations were used as test cases for the numerical studies. Rectangular hydrofoils of $AR = 1, 6$, and 10 provided most of the stability information. An $AR = 6.1$ foil with a sweep angle Λ of 15

deg and a taper ratio τ of 0.25 represented the effects of sweep and taper. The foils were given a NACA $a = 1.0$ mean line to study camber loading predictions. This choice of camber was based on the presence of the NACA $a = 1.0$ camber line on most of the hydrofoil models for which data are available.

To summarize the results, the degree of numerical stability that could be achieved was quite limited, being more than one but less than three significant figures. More precisely, the calculations for the $AR = 10$ hydrofoil had a residual instability of 0.4 to 9 percent, depending on the load coefficient considered. Most coefficients became more stable at lower aspect ratio; at $AR = 1$ the instability was about 1 percent for all coefficients. Results for the swept, tapered planform were similar, except for the pitching moment slope which had an instability of 27 percent. Specific effects of the numerical parameters and model configurations will be discussed in the following sections.

NUMERICAL STABILITY OF THE STEADY LOADING CALCULATION

A large number of calculations were performed for hydrofoils under steady flow conditions. Camber-induced loading was investigated separately from loading due to angle of attack. Camber loading is expressed in terms of the coefficients $C_L(\alpha = 0)$ and $C_M(\alpha = 0)$. Angle of attack loading is presented as the coefficient slopes $C_{L\alpha}(\alpha = 0)$ and $C_{M\alpha}(\alpha = 0)$.

Number of Chordwise Pressure Modes, NOLT

The stability of the steady loading calculation was extremely sensitive to the number of chordwise pressure modes used. The calculated coefficients are shown in Figures 2 through 13.

As the number of pressure modes was initially increased, most values of lift and pitching moment began to approach a stable condition in an almost monotonic manner, as shown in Figures 2 through 7 and 11 through 13. A somewhat different pattern was followed by the lift slope, which oscillated with decreasing amplitude as it approached an apparently stable value;

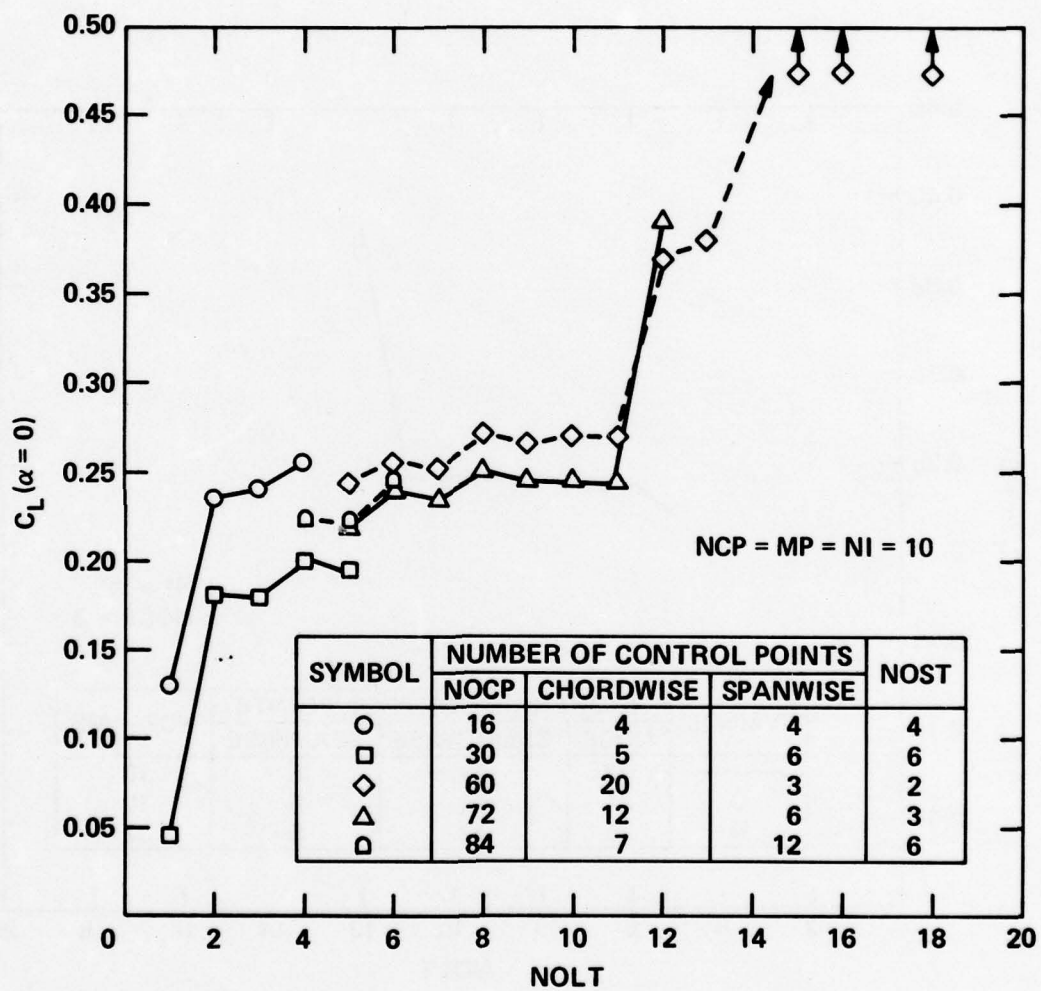


Figure 2 - The Steady Lift Coefficient $C_L(\alpha = 0)$ as a Function of the Number of Chordwise Modes NOLT for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

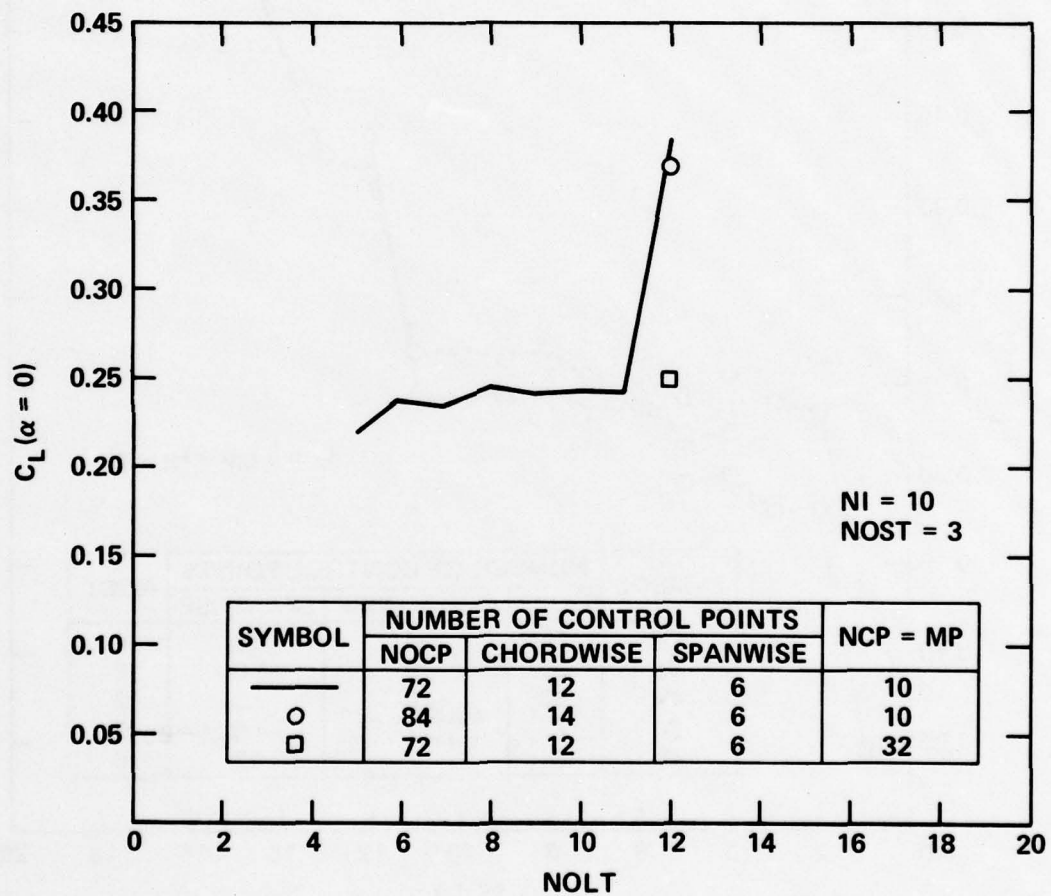


Figure 3 - The Effect of the Number of Chordwise Integration Steps NCP and MP on the Steady Lift Coefficient $C_L(\alpha = 0)$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

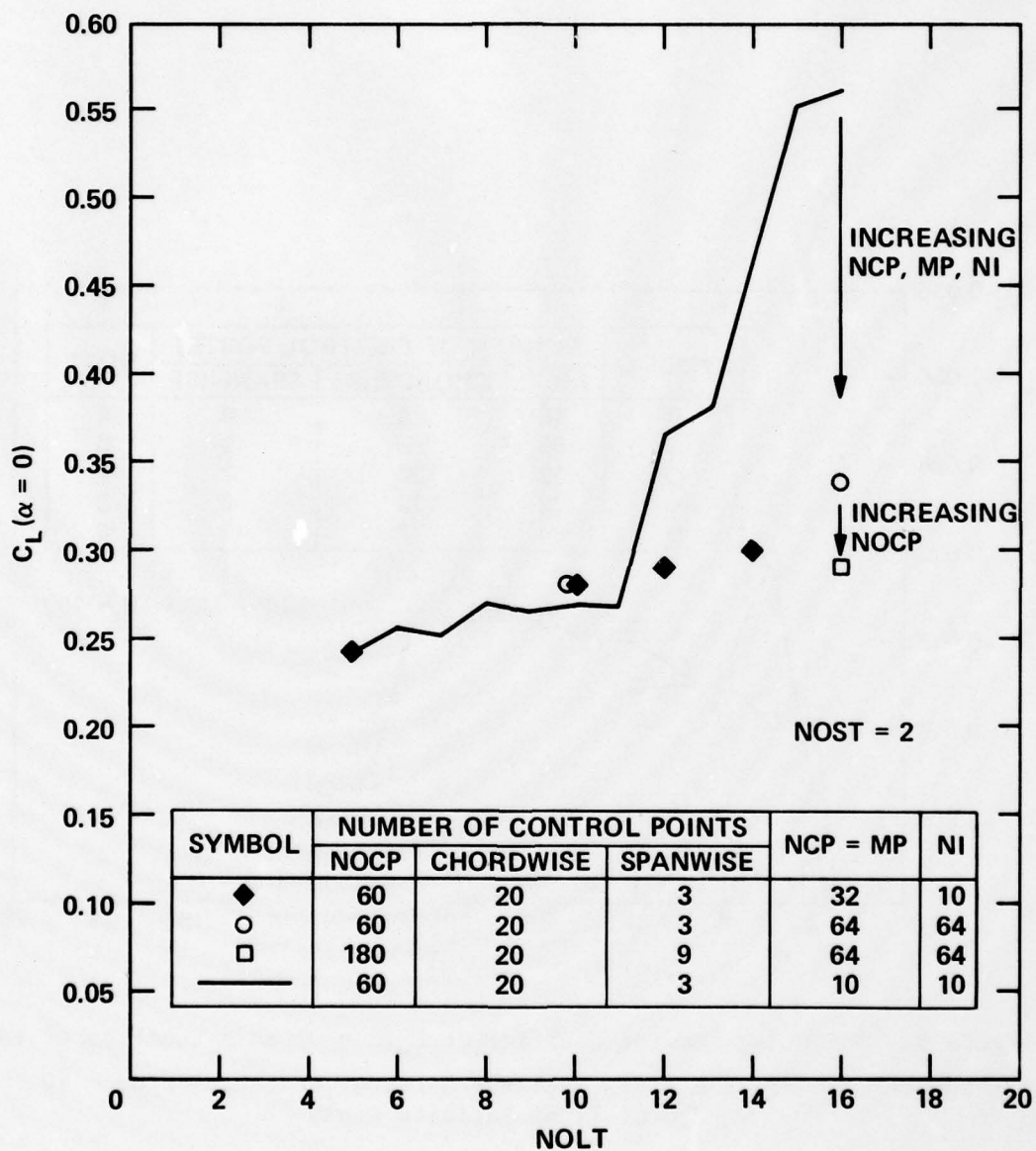


Figure 4 - The Effect of the Number of Integration Steps NCP, MP, and NI and Control Points NOCP on the Steady Lift Coefficient $C_L(\alpha = 0)$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

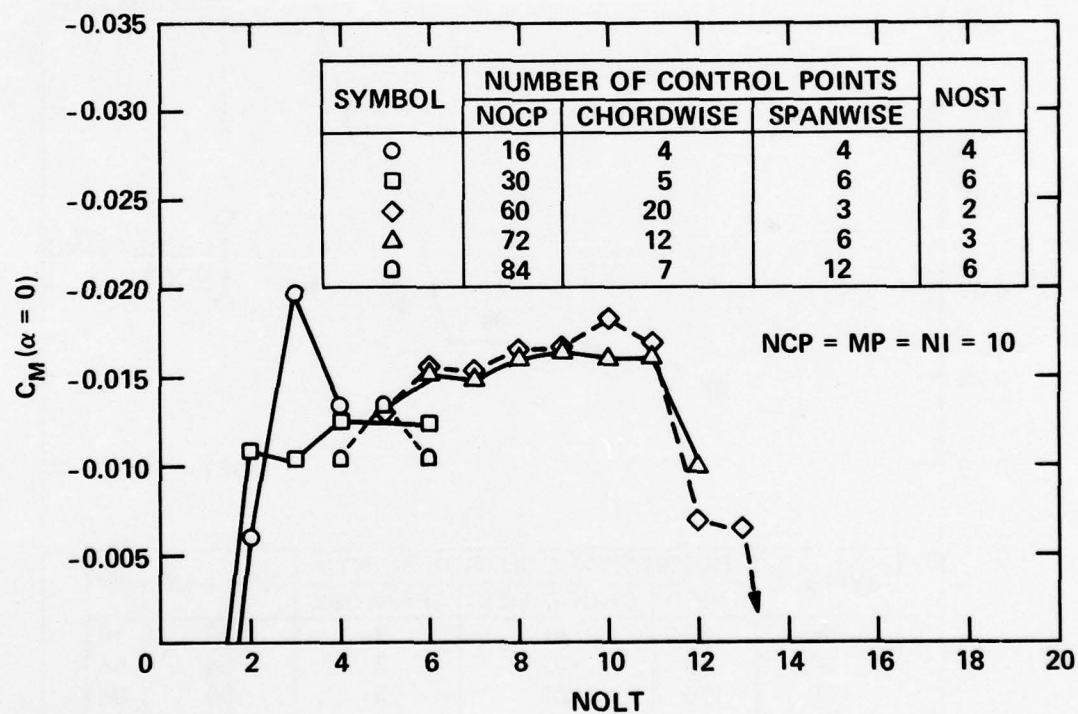


Figure 5 - The Steady Moment Coefficient $C_M(\alpha = 0)$ as a Function of the Number of Chordwise Modes NOLT for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

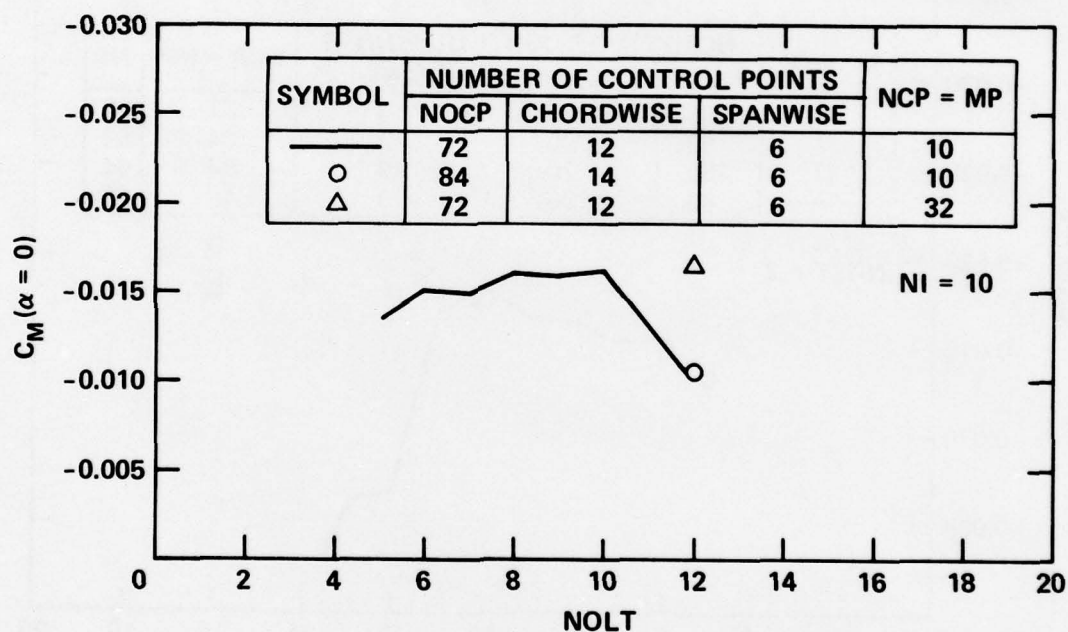


Figure 6 - The Effect of the Number of Chordwise Integration Steps NCP and MP on the Steady Moment Coefficient $C_M(\alpha = 0)$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

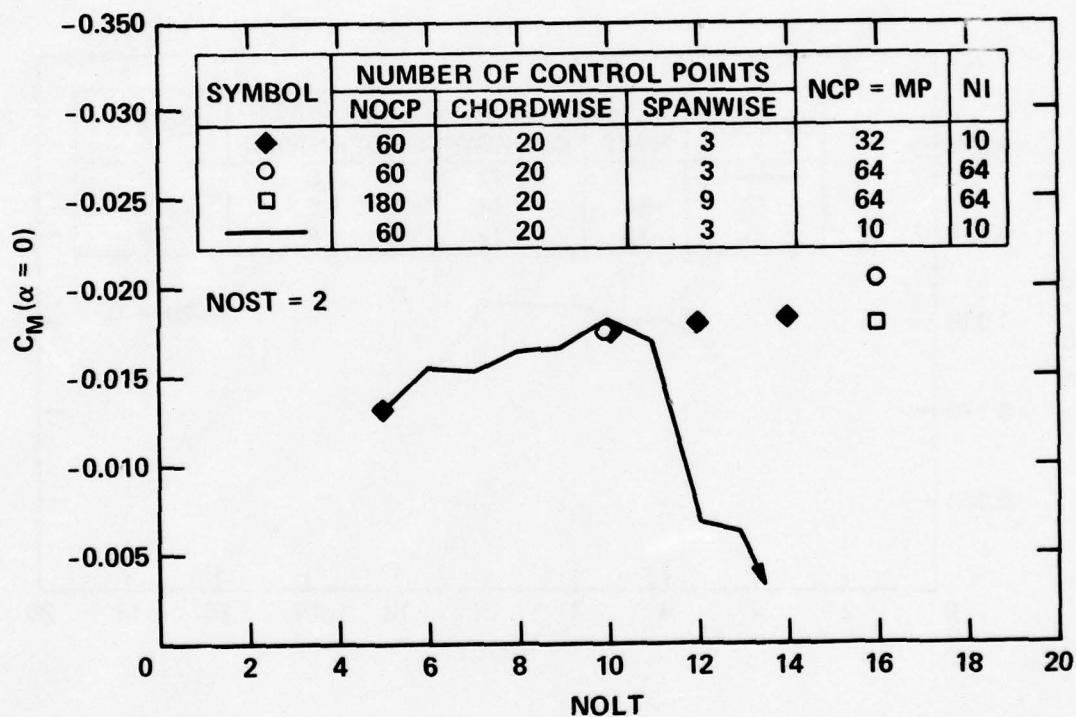


Figure 7 - The Effect of the Number of Integration Steps NCP, MP, and NI and Control Points NOCP on the Steady Moment Coefficient $C_M(\alpha = 0)$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

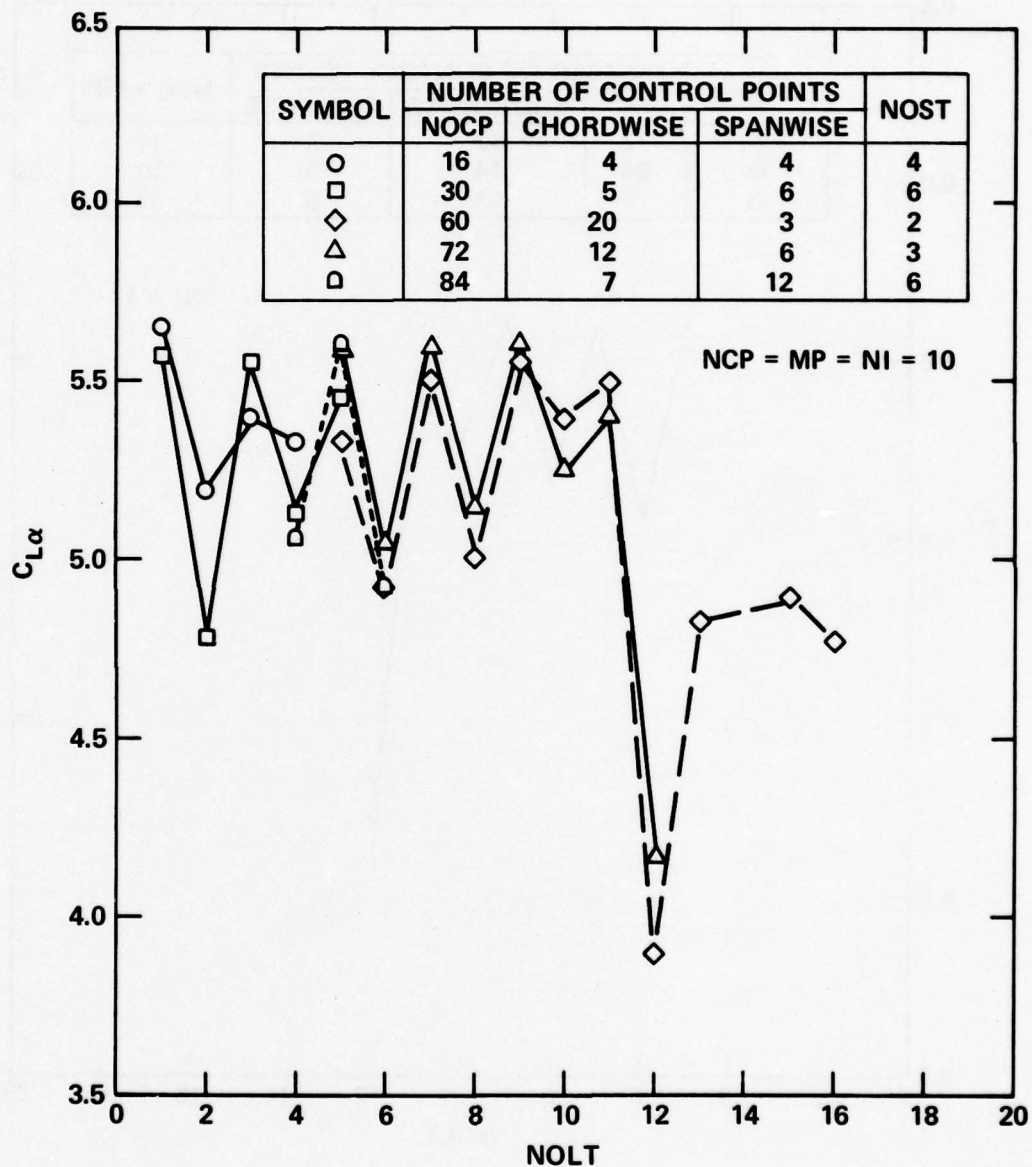


Figure 8 - The Steady Lift Coefficient Slope $C_{L\alpha}$ as a Function of the Number of Chordwise Modes NOLT for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

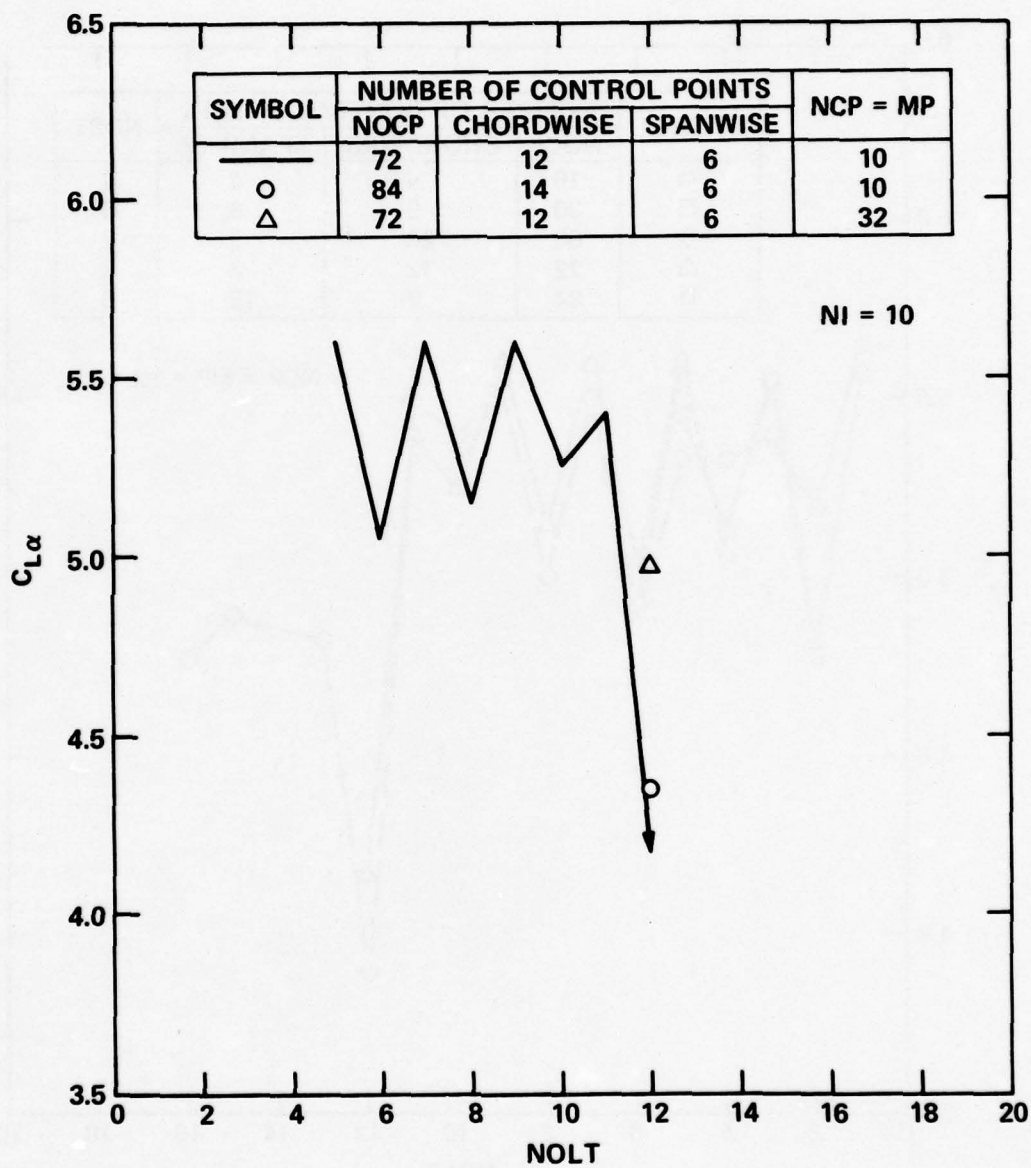


Figure 9 - The Effect of the Number of Chordwise Integration Steps NCP and MP on the Steady Lift Coefficient Slope $C_{L\alpha}$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

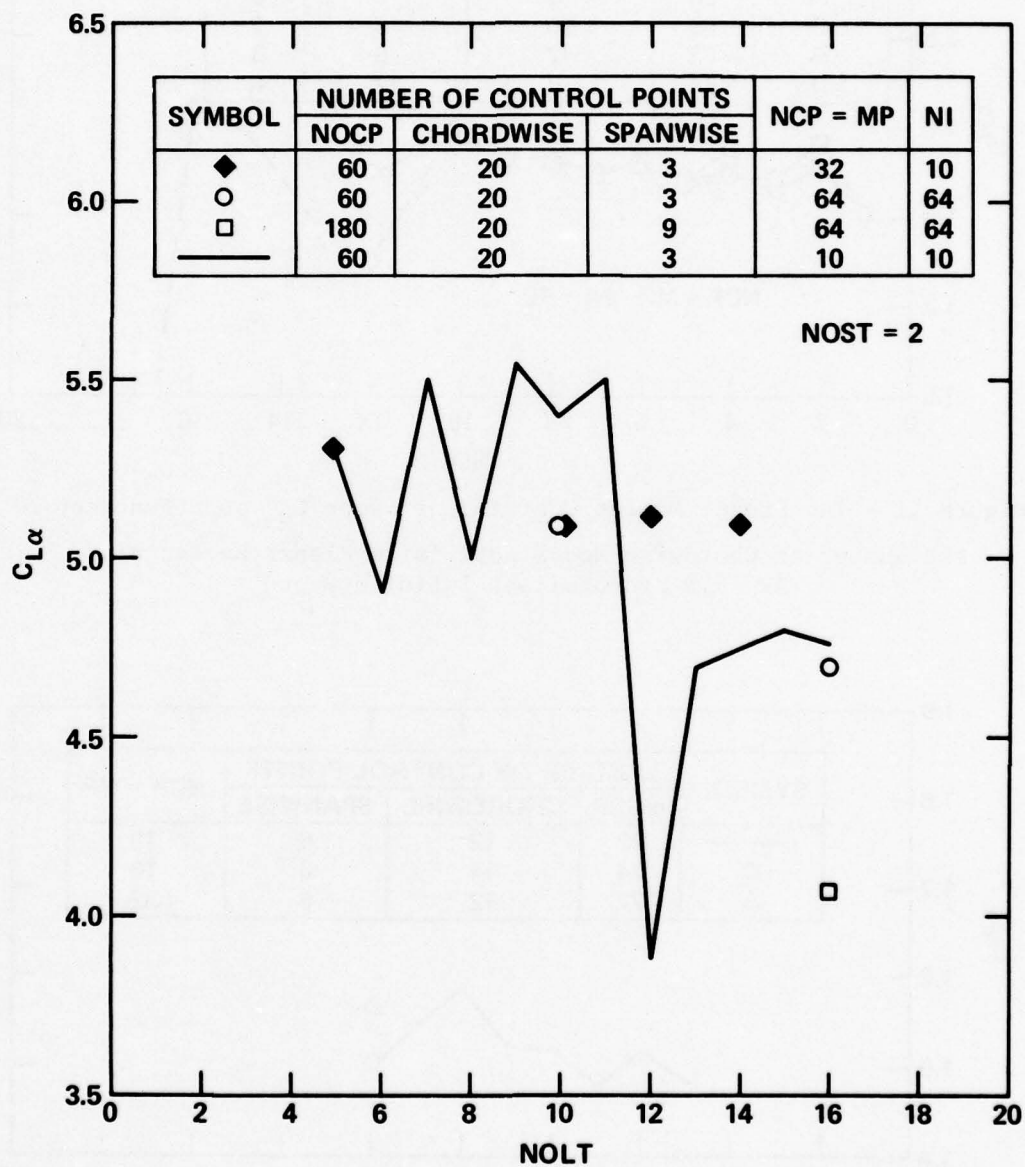


Figure 10 - The Effect of the Number of Integration Steps NCP, MP, and NI and Control Points NOCP on the Steady Lift Coefficient Slope $C_{L\alpha}$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

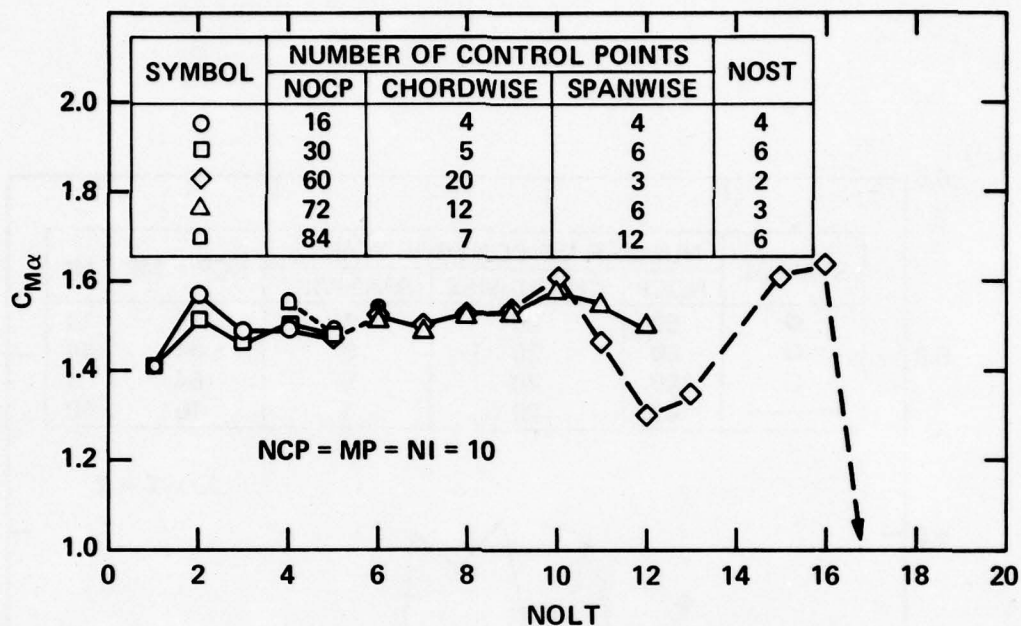


Figure 11 - The Steady Moment Coefficient Slope $C_{M\alpha}$ as a Function of the Number of Chordwise Modes $NOLT$ for a Planar Rectangular $AR = 10$ Hydrofoil at Infinite Depth

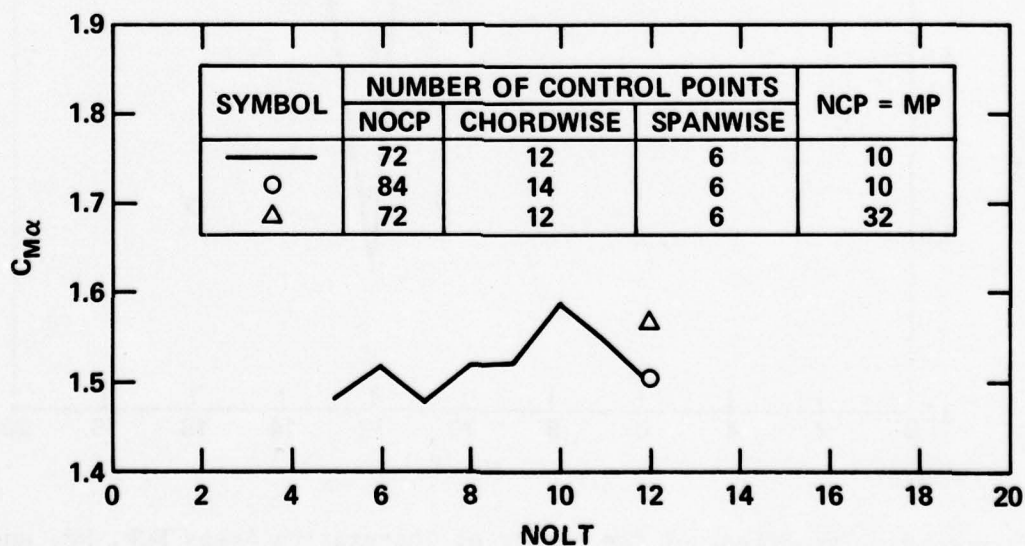


Figure 12 - The Effect of the Number of Chordwise Integration Steps NCP and MP on the Steady Moment Coefficient Slope $C_{M\alpha}$ for a Planar Rectangular $AR = 10$ Hydrofoil at Infinite Depth

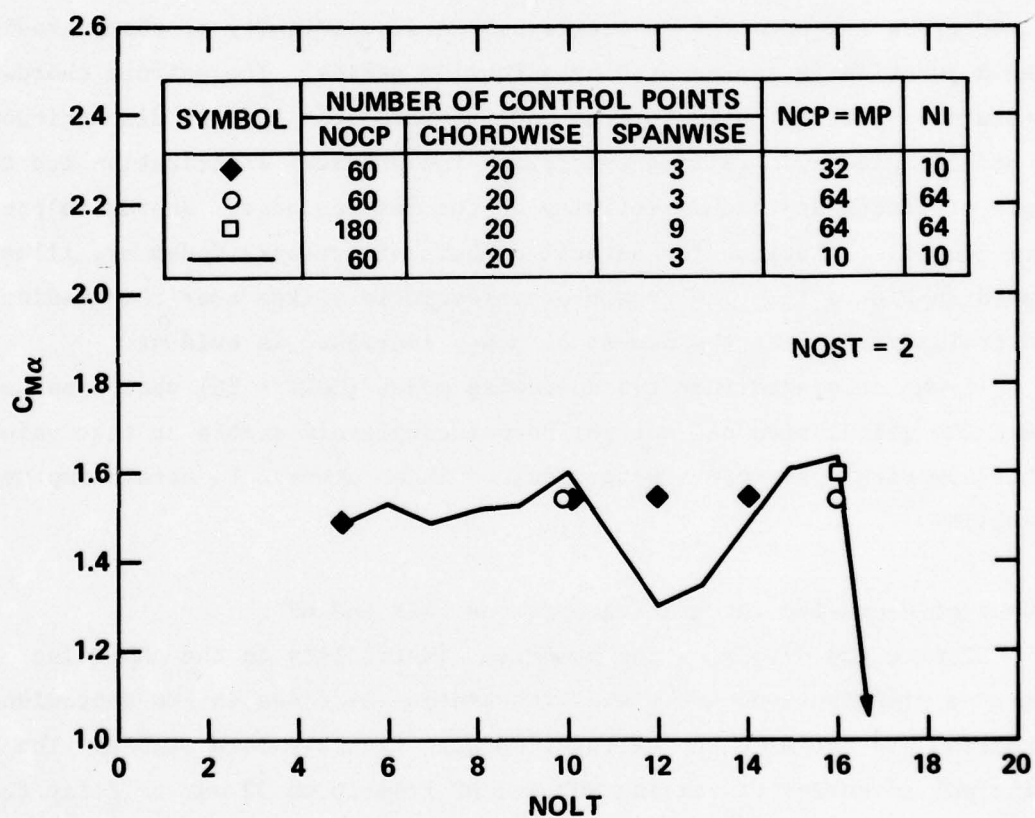


Figure 13 - The Effect of the Number of Integration Steps NCP, MP, and NI and Control Points NOCP on the Steady Moment Coefficient Slope $C_{M\alpha}$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

see Figures 8 through 10. These differences are attributed to the different combination of pressure modes required to represent the chordwise pressure distribution arising from the two types of downwash.

Before the calculation had become completely stable, however, the coefficients abruptly shifted away from the approaching stable values and, thereafter, exhibited gross instability. This latter instability was discovered upon examination of the calculated chordwise pressure distribution to be an occurrence of the Gibbs phenomenon. The Gibbs phenomenon refers to the gross inaccuracy that occurs near a discontinuity or sharp gradient when a function is represented by a Fourier series. The uniform chordwise pressure jump distribution of the NACA $a = 1.0$ mean line is discontinuous at both leading and trailing edges, and the pressure distribution due to angle of attack approaches infinity at the leading edge. Chordwise pressure jump distributions for several numbers of pressure modes are illustrated in Figure 14. The growth of unrealistic spikes near the leading and trailing edges as the number of modes increases is evident.

It was concluded that ten chordwise modes ($NOLT = 10$) should be used. Since the calculation had not yet become completely stable at that value, other numerical parameters were examined in an attempt to attain improved stability.

Number of Chordwise Integration Stations, NCP and MP

Despite the origin of the numerical instability in the chordwise pressure distribution, additional integration stations in the chordwise direction did not make the calculation significantly more stable. The principal advantage of raising NCP and MP from 10 to 32 was to delay the complete breakdown in the convergence process; this effect can be seen most clearly in Figures 4, 7, 10, and 13. The calculation continued to be unstable at $NCP = MP = 32$, however, as is apparent in the figures and Table 1. A further increase in NCP and MP to 64 appeared to have a stabilizing effect on the camber-induced loading (Figures 4 and 7) but a destabilizing effect on the loading slopes (Figures 10 and 13). These unsuccessful results with larger numbers of chordwise integration stations led to the selection of $NCP = MP = 10$ as baseline values.

Figure 14 - Numerical Instability of the Chordwise Distribution of Lift at the Midspan of an AR = 10 Rectangular Hydrofoil at Infinite Depth

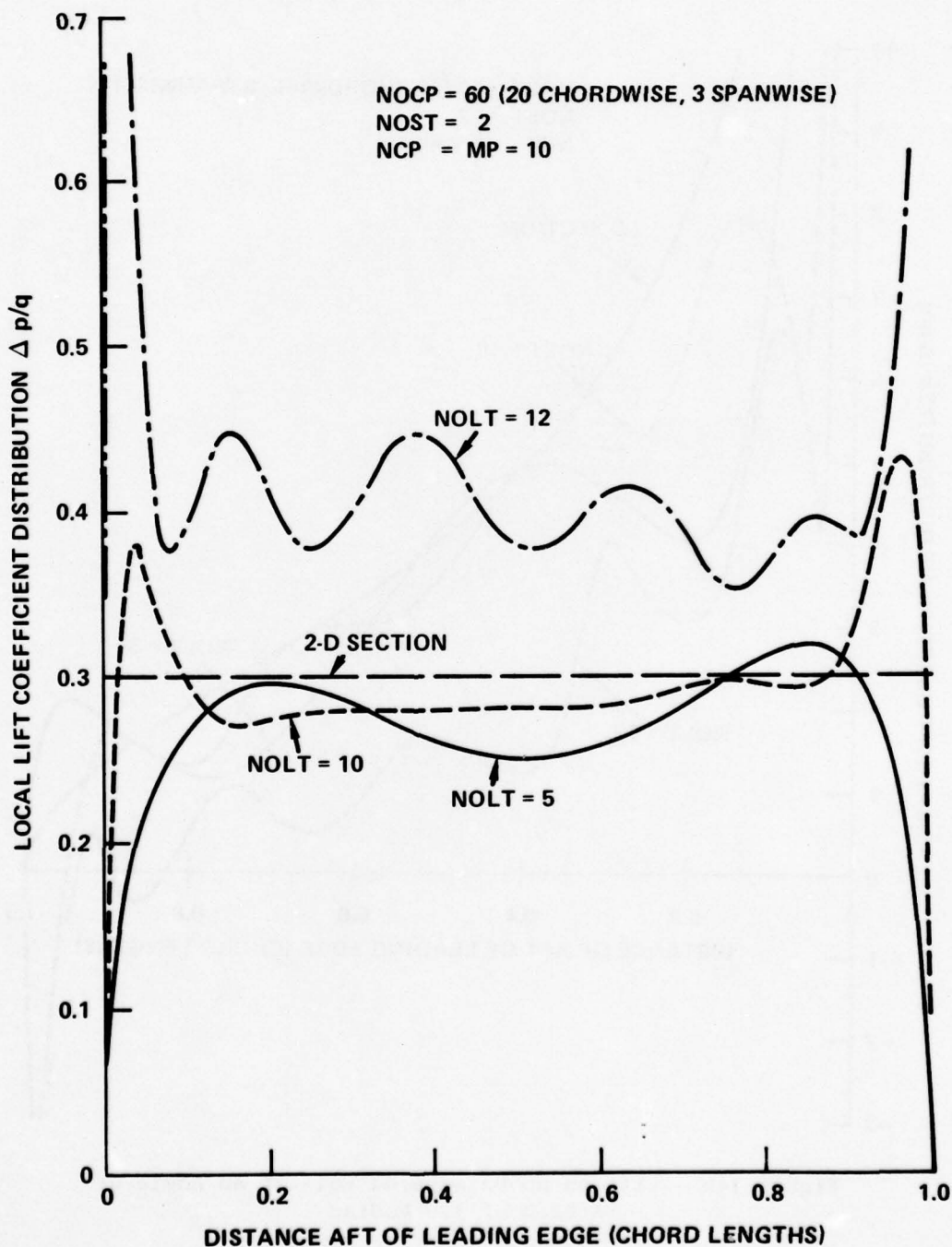


Figure 14a - Lift due to a NACA $a = 1.0$ ($C_l = 0.3$) Camber Line

Figure 14 (Continued)

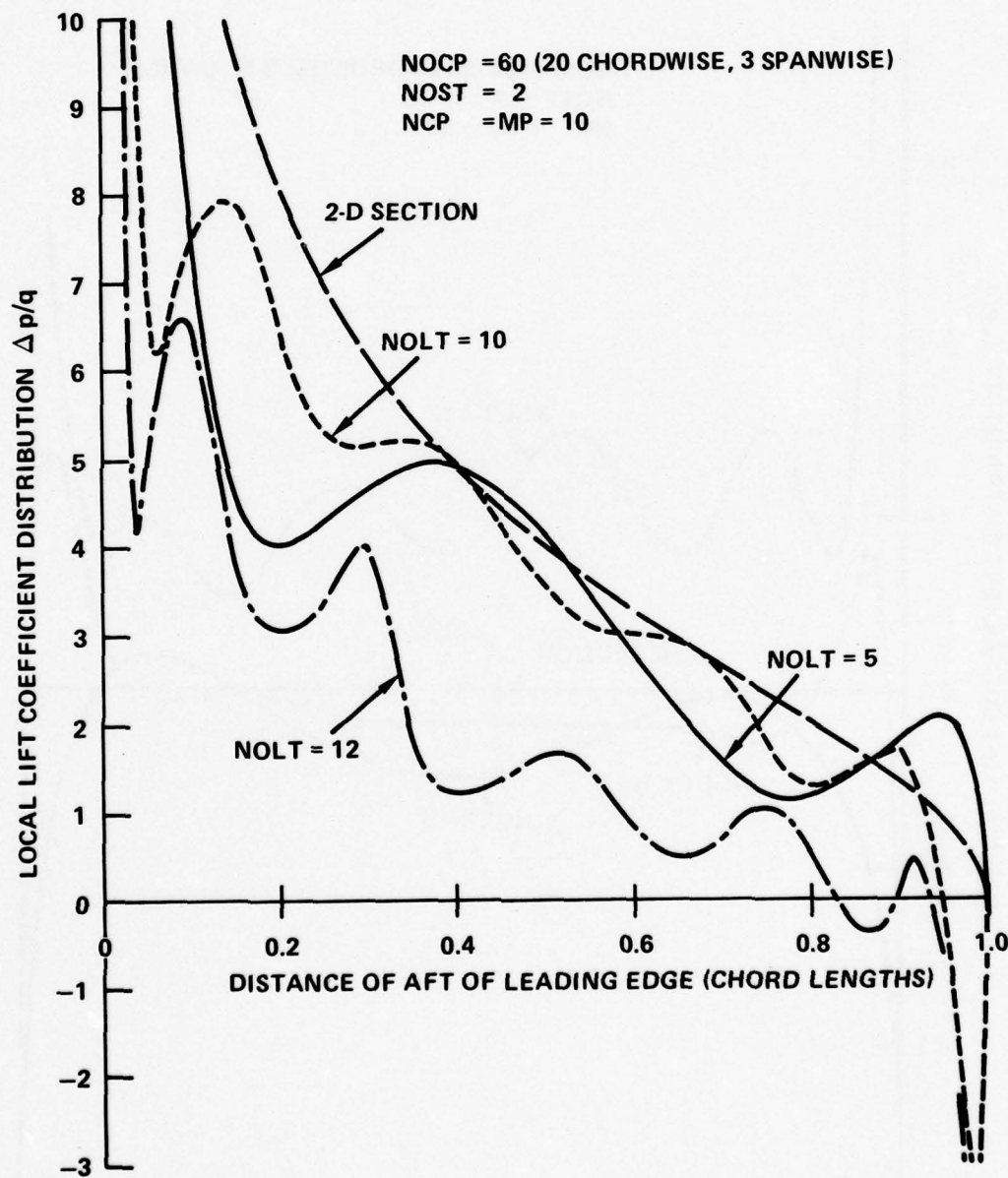


Figure 14b - Lift on an Uncambered Foil at an Angle of Attack of 1.0 Radian

TABLE 1 - NUMERICAL STABILITY OF CALCULATED LOAD COEFFICIENTS FOR A PLANAR RECTANGULAR HYDROFOIL AT INFINITE DEPTH

| AR | NCP,MP | NOLT | $C_L(\alpha=0)$ | $C_M(\alpha=0)$ | $C_{L\alpha}(\text{rad}^{-1})$ | $C_{M\alpha}(\text{rad}^{-1})$ | Percent Change | | | | |
|----|--------|------|-----------------|-----------------|--------------------------------|--------------------------------|----------------|--------------|----------------------|----------------------|---|
| | | | | | | | ΔC_L | ΔC_M | $\Delta C_{L\alpha}$ | $\Delta C_{M\alpha}$ | |
| 10 | 10 | 5 | 0.2423 | -0.01312 | 5.331 | 1.471 | - | - | - | - | |
| | | 6 | 0.2566 | -0.01552 | 4.929 | 1.534 | +5.9 | -18.3 | -7.5 | +4.3 | |
| | | 7 | 0.2526 | -0.01517 | 5.497 | 1.490 | -1.6 | +2.3 | +11.5 | -2.9 | |
| | | 8 | 0.2700 | -0.01654 | 5.013 | 1.526 | +6.9 | -9.0 | -8.8 | +2.4 | |
| | | 9 | 0.2656 | -0.01660 | 5.541 | 1.539 | -1.6 | -0.4 | +10.5 | +0.9 | |
| | | 10 | 0.2693 | -0.01835 | 5.394 | 1.607 | +1.4 | -10.5 | -2.7 | +4.4 | |
| | | 11 | 0.2681 | -0.01679 | 5.498 | 1.465 | -0.4 | +8.5 | +1.9 | -8.9 | |
| | | 12 | 0.3670 | -0.00692 | 3.876 | 1.297 | +36.9 | +58.8 | -29.5 | -11.5 | |
| | | 32 | 10 | 0.2797 | -0.01746 | 5.082 | 1.543 | - | - | - | - |
| | | 11 | 0.2764 | -0.01721 | 5.487 | 1.516 | -1.2 | +1.4 | +8.0 | -1.8 | |
| | | 12 | 0.2895 | -0.01805 | 5.112 | 1.537 | +4.7 | -4.9 | -6.8 | +1.4 | |
| | | 13 | 0.2884 | -0.01795 | 5.368 | 1.525 | -0.4 | +0.6 | +5.0 | -0.8 | |
| | | 14 | 0.2995 | -0.01861 | 5.087 | 1.539 | +3.8 | -3.7 | +5.2 | +0.9 | |
| | | 6 | 10 | 8 | 0.2139 | -0.01904 | 4.234 | 1.250 | - | - | - |
| 9 | 0.2094 | | | -0.01885 | 4.581 | 1.238 | -2.1 | +1.0 | +8.2 | -1.0 | |
| 10 | 0.2184 | | | -0.02024 | 4.338 | 1.274 | +4.3 | -7.4 | -5.3 | +2.9 | |
| 11 | 0.2150 | | | -0.01947 | 4.566 | 1.223 | -1.6 | +3.8 | +5.3 | -4.0 | |
| 1 | 10 | 8 | 0.08276 | -0.02435 | 1.454 | 0.4944 | - | - | - | - | |
| | | 9 | 0.08196 | -0.02416 | 1.471 | 0.4904 | -1.0 | +0.8 | +1.2 | -0.8 | |
| | | 10 | 0.08420 | -0.02486 | 1.456 | 0.4953 | +2.7 | -2.9 | -1.0 | +1.0 | |
| | | 11 | 0.08354 | -0.02462 | 1.470 | 0.4901 | -0.8 | +1.0 | +1.0 | -1.0 | |

NOTE:

The above results were obtained with 60 control points (NOCP=60) arranged as in Table 2. Also, NOST=2 and NI=10.

Number of Collocation Points, NOCP

In general, a large number of collocation or control points are required in the chordwise direction, while relatively few suffice in the spanwise direction. Exploratory calculations were made using a basic array of 20 chordwise and 3 spanwise rows of control points (NOCP = 60) located as given in Table 2. Evenly distributed chordwise rows of points were removed or spanwise rows added as required.

TABLE 2 - INPUT PARAMETER BASELINE VALUES REQUIRED
FOR APPROXIMATE NUMERICAL STABILITY OF THE
STEADY LOADING CALCULATION

| Program Variable | Input Value |
|------------------|---|
| NOCP | 60 |
| NOLT | 10 |
| NOST | 2 |
| NCP | 10 |
| MP | 10 |
| NI | 10 |
| XOC | 0.025,0.05,0.1,0.15,0.2,0.25,0.3,0.35,0.4, 0.45,0.55,0.6,0.65,0.7,0.75,0.8,0.85,0.9, 0.95,0.975 |
| SOS | 0.35,0.65,0.9 |

Two minimum conditions were found necessary to avoid marked instabilities in the calculation: the number of rows of control points in both chordwise and spanwise directions had to exceed the number of pressure modes in the respective directions. This result is indicated in Table 3. The effects of additional control points beyond this minimum number are shown

TABLE 3 - EFFECT OF CONTROL POINT ARRANGEMENT AND NUMBER OF PRESSURE MODES
ON THE NUMERICAL STABILITY OF STEADY LIFT COEFFICIENT C_L ($\alpha=0$)

(AR=10 rectangular foil; NACA 16-300 ($a=1.0$) profile; $h/c = \infty$; NCP=MP=32; NI=10)

| Number of Control Points (NOCP) | Number of Chordwise Rows of Control Points | Number of Chordwise Pressure Modes (NOLT) | Number of Spanwise Rows of Control Points | Number of Spanwise Pressure Modes (NOST) | Lift Coefficient C_L |
|---------------------------------|--|---|---|--|------------------------|
| 60 | 20 | 8 | 3 | 4 | Unstable |
| 60 | 20 | 8 | 3 | 2 | Stable |
| 84 | 7 | 13 | 12 | 4 | Unstable |
| 84 | 7 | 10 | 12 | 4 | Unstable |
| 84 | 7 | 7 | 12 | 4 | Stable |
| 84 | 7 | 4 | 12 | 4 | Stable |

in Figures 15 through 18. Adding rows of control points in the chordwise direction improved the stability of the calculation, while increasing the number of spanwise rows of control points beyond the minimum had no effect. The calculations showed that 20 chordwise and 3 spanwise rows were sufficient to eliminate the more severe instabilities in the load coefficients.

Number of Spanwise Pressure Modes, NOST

Two spanwise pressure modes (NOST = 2) were sufficient for good numerical stability, as shown in Figures 19 through 22. This result occurred because the spanwise foil loading closely resembled the first, elliptically-shaped pressure mode. (The modes used for this test case were the same as those in Subroutine FUNCTN in Programs 2 and 3, Appendix C.) Note that other spanwise loading conditions may require additional spanwise pressure modes for accurate representation.

Number of Spanwise Integration Stations, NI

This variable was not extensively evaluated, in view of the relative insensitivity of the calculated coefficients to the number of spanwise pressure modes. Only two calculations were made with a value of NI other than 10. In these calculations, shown in Figures 4, 7, 10, and 13, NI was increased from 10 to 64 while NCP and MP were simultaneously increased from 32 to 64. Since the results did not change noticeably, it was concluded that 10 spanwise integration stations (NI = 10) are adequate.

Effect of Foil Aspect Ratio

The stability of the calculation improved as aspect ratio decreased. As derived from Table 1, calculations made at aspect ratios of 10, 6, and 1 had the following ranges of variation when the value of NOLT was increased from 10 to 11.

| Aspect Ratio | Range of Change in Load Coefficients (percent) |
|--------------|--|
| 10 | 0.4 to 8.9 |
| 6 | 1.6 to 5.3 |
| 1 | 0.8 to 1.0 |

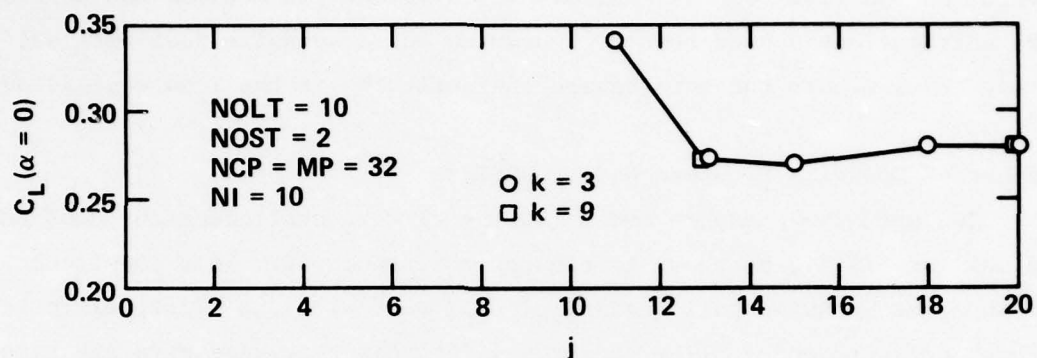


Figure 15 - The Effect of the Number of Chordwise Control Points j and Spanwise Control Points k on the Steady Lift Coefficient $C_L(\alpha = 0)$ for a Planar Rectangular $AR = 10$ Hydrofoil at Infinite Depth

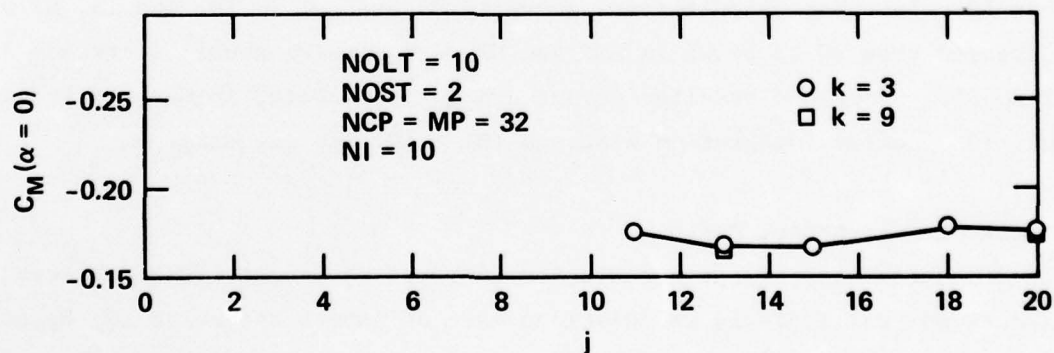


Figure 16 - The Effect of the Number of Chordwise Control Points j and Spanwise Control Points k on the Steady Moment Coefficient $C_M(\alpha = 0)$ for a Planar Rectangular $AR = 10$ Hydrofoil at Infinite Depth

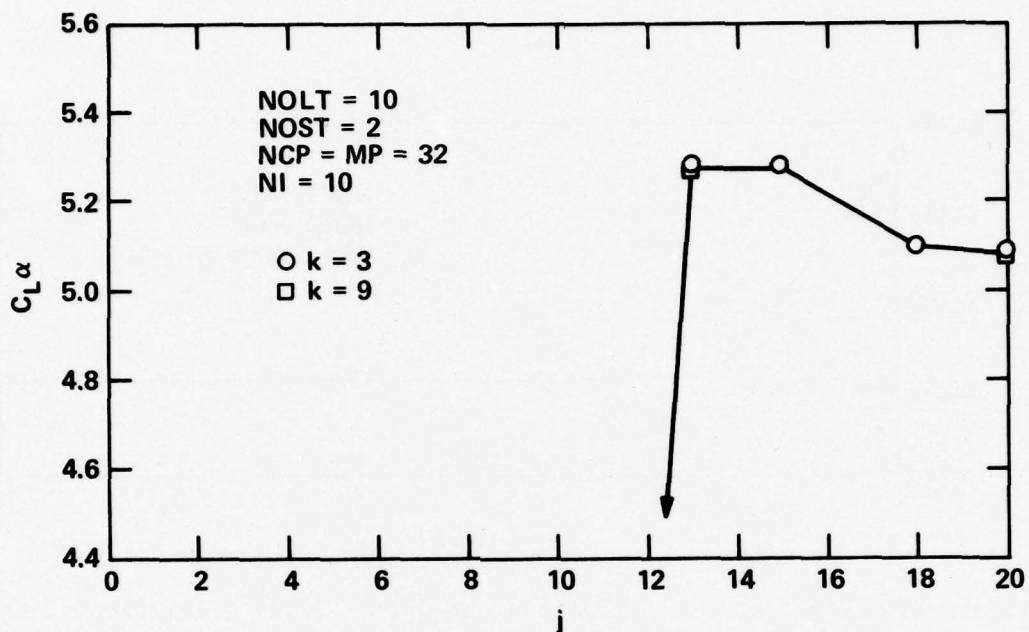


Figure 17 - The Effect of the Number of Chordwise Control Points j and Spanwise Control Points k on the Steady Lift Coefficient Slope $C_{L\alpha}$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

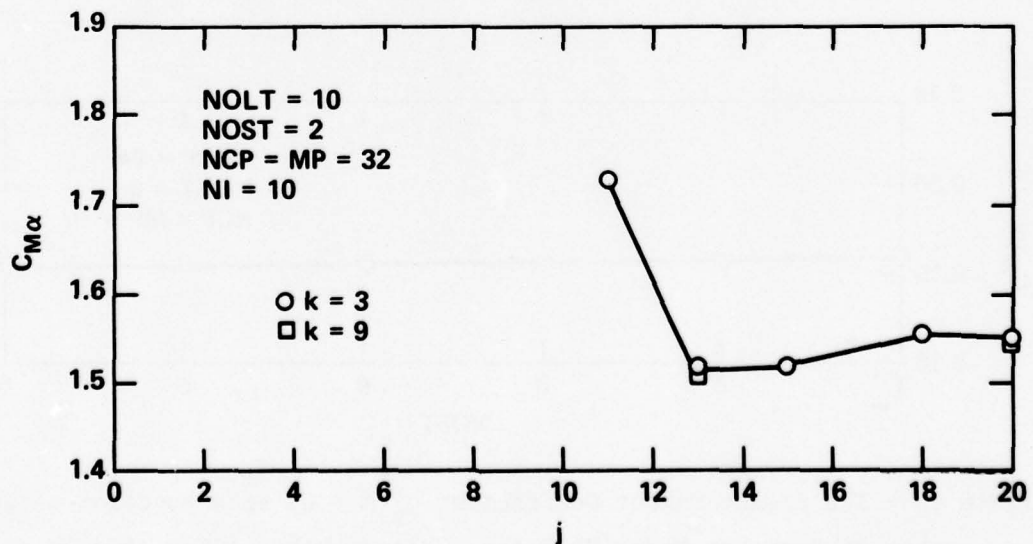


Figure 18 - The Effect of the Number of Chordwise Control Points j and Spanwise Control Points k on the Steady Moment Coefficient Slope $C_{M\alpha}$ for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

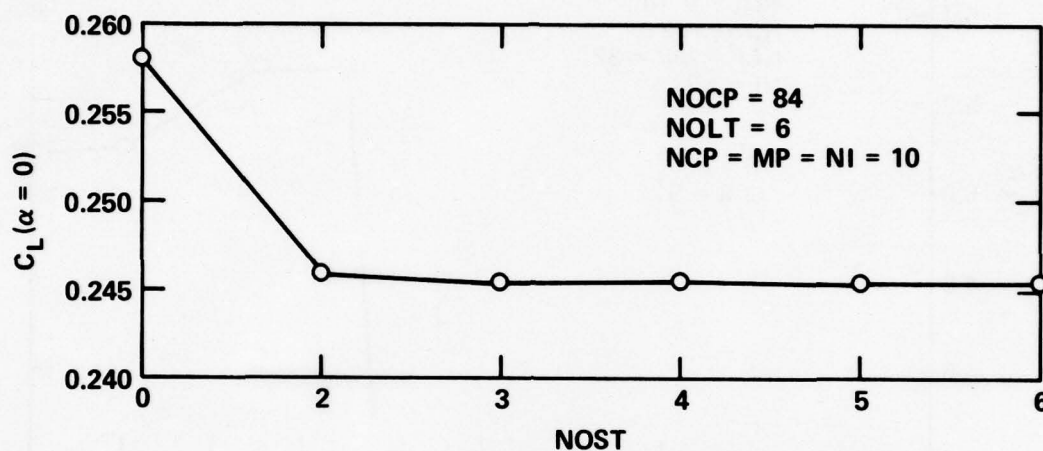


Figure 19 - The Steady Lift Coefficient $C_L(\alpha = 0)$ as a Function of the Number of Spanwise Modes NOST for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

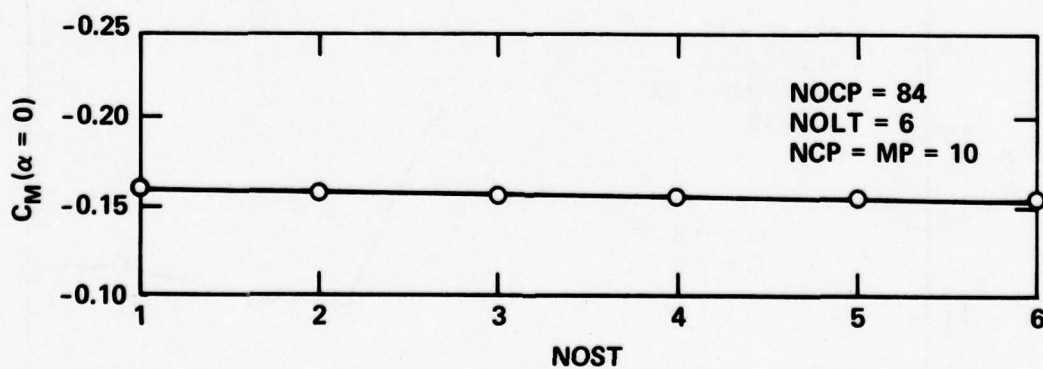


Figure 20 - The Steady Moment Coefficient $C_M(\alpha = 0)$ as a Function of the Number of Spanwise Modes NOST for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

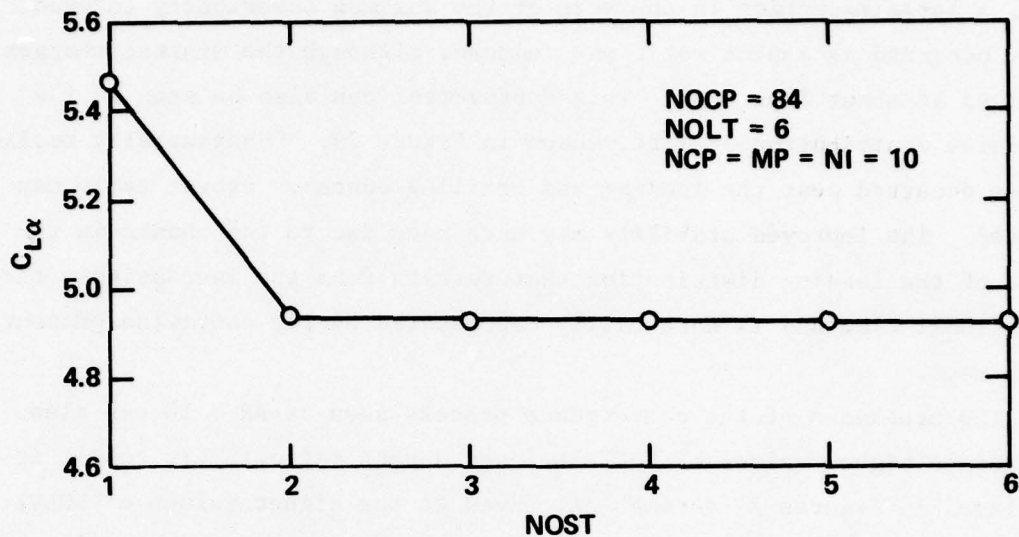


Figure 21 - The Steady Lift Coefficient Slope $C_{L\alpha}$ as a Function of the Number of Spanwise Modes NOST for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

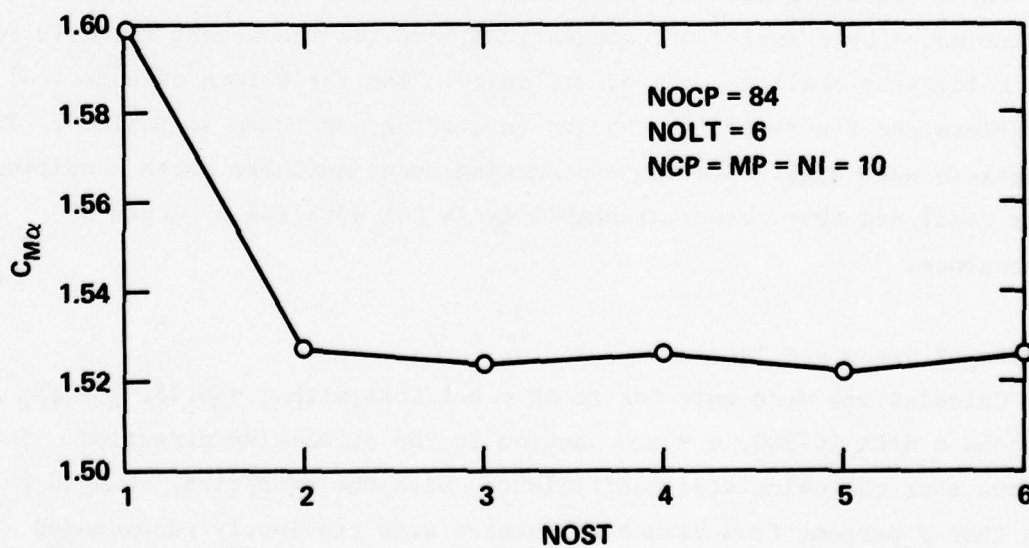


Figure 22 - The Steady Moment Coefficient Slope $C_{M\alpha}$ as a Function of the Number of Spanwise Modes NOST for a Planar Rectangular AR = 10 Hydrofoil at Infinite Depth

Thus, a large reduction in the size of the maximum numerically induced shift occurred as aspect ratio was reduced, although the minimum changes remained at about 1 percent. This improvement can also be seen in the chordwise distribution of lift, shown in Figure 23. Substantially smaller spikes occurred near the leading and trailing edges as aspect ratio was reduced. The improved stability may have been due to the change in the shape of the loading distribution that results from the increasingly three-dimensional flow and is more easily represented by the chordwise pressure modes used.

The breakdown of the convergence process seen at $AR = 10$ was also delayed to higher values of NOLT at lower aspect ratio. This result is displayed in Figures 24 through 31. Even at the higher values of NOLT, however, the calculated coefficients continued to vary substantially rather than become stable. Since the sensitivity to numerical parameters decreased with decreasing aspect ratio, it was concluded that the previously selected parameter values were adequate for aspect ratios of less than 10.

Effect of Finite Depth

The influence of shallow submergence on the numerical representation was estimated by a series of calculations made for the aspect ratio 10 foil at a relatively shallow depth of 0.2 chord. The variations of numerical parameters and the resulting changes in loading are shown in Table 4. The variations were similar to those occurring under infinite depth conditions. It is concluded that numerical stability is not affected by depth of submergence.

Effects of Sweep and Taper

Calculations were made for an $AR = 6.1$ foil with $\tau = 0.25$, $\Lambda = 15$ deg, and a NACA 16-300, $a = 1.0$ section in the streamwise direction. Table 5 shows that the calculated coefficients, with one exception, changed by less than 7 percent from values calculated with previously recommended parameter values, as the numerical parameters varied. However, the exception, $C_{M\alpha}$, oscillated by up to 27 percent as NOLT varied. This large

Figure 23 - The Effect of Aspect Ratio on the Chordwise Distribution of Lift at the Midspan of a Rectangular Hydrofoil at Infinite Depth

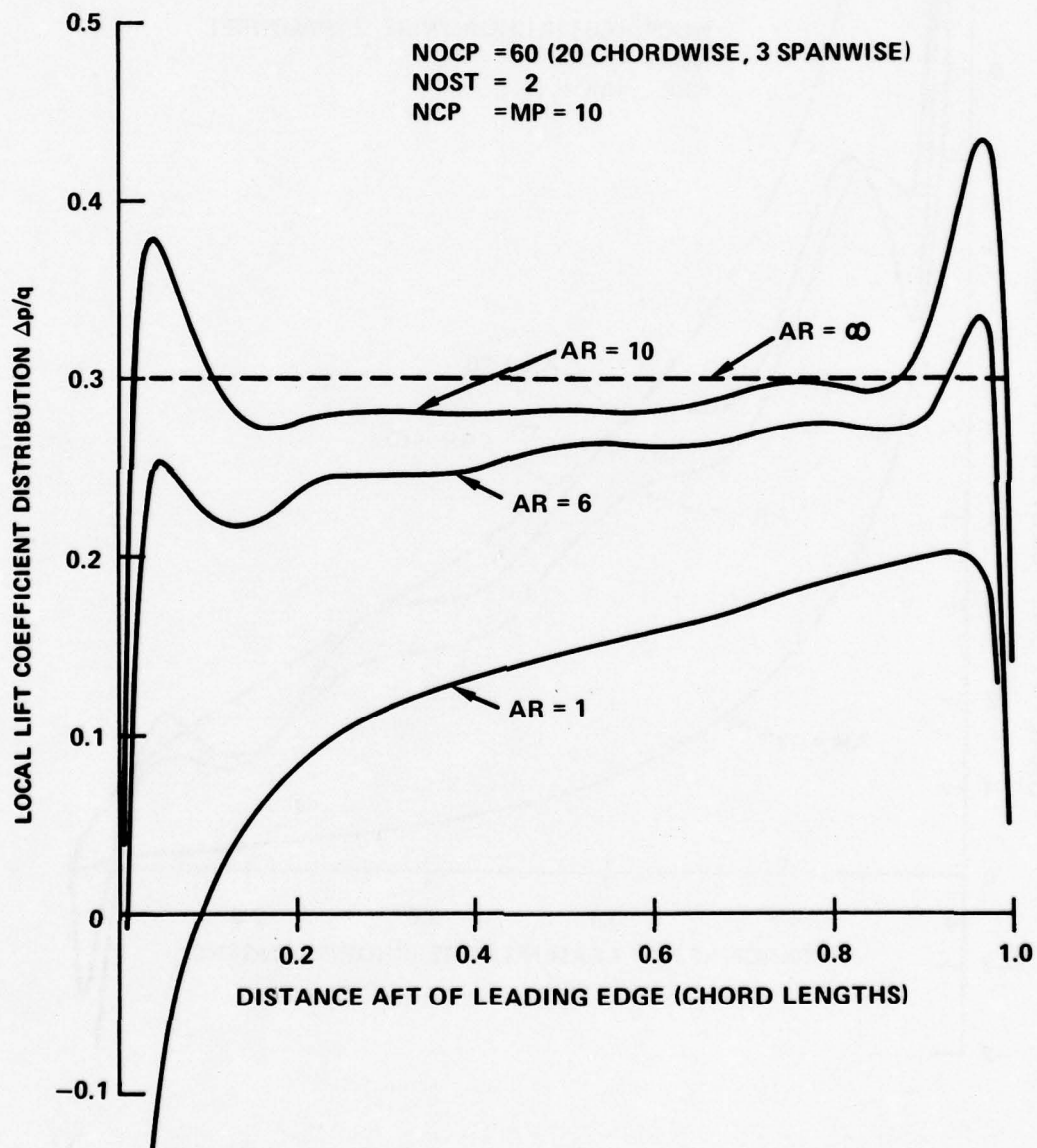


Figure 23a - Lift due to a NACA $a = 1.0$ ($C_l = 0.3$) Camber Line

Figure 23 (Continued)

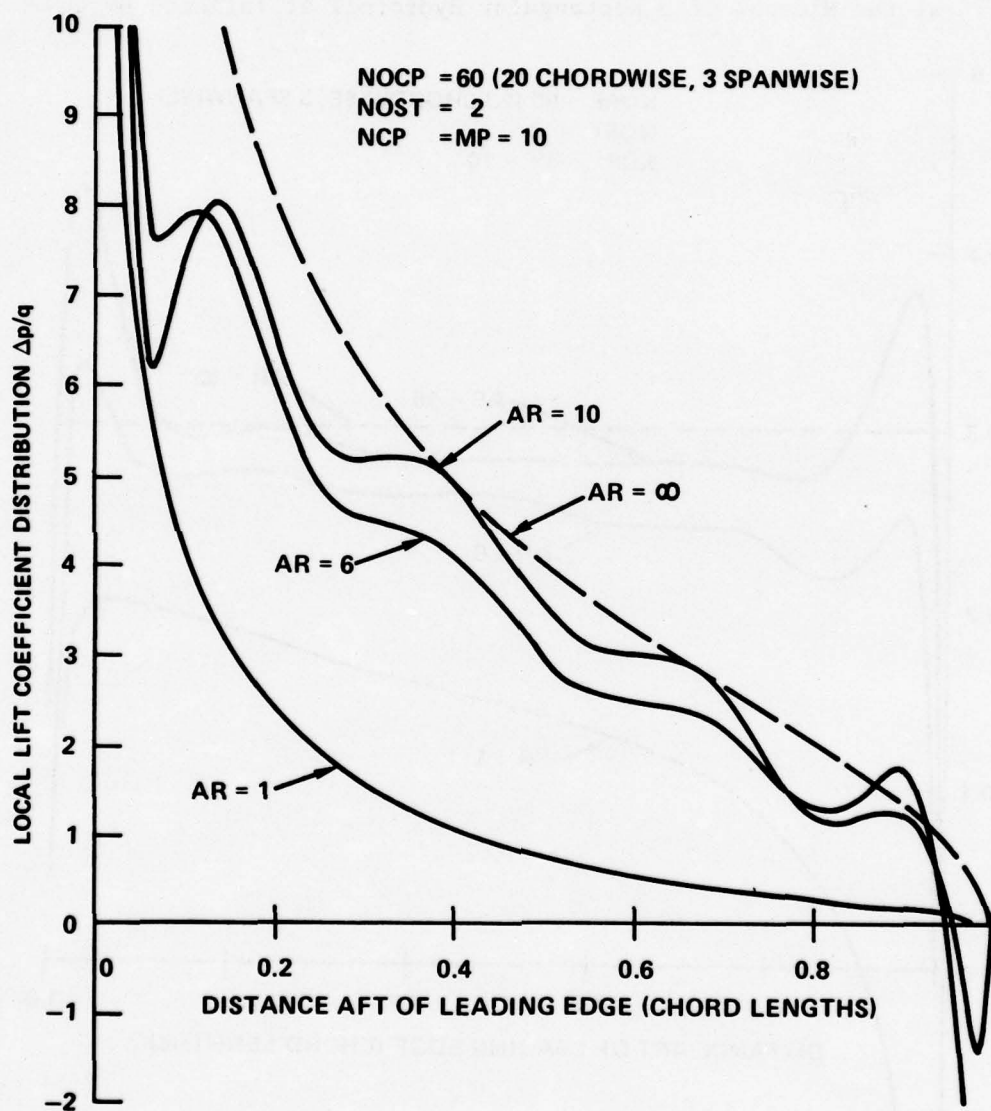


Figure 23b - Lift on an Uncambered Foil at an Angle of Attack of 1.0 Radian

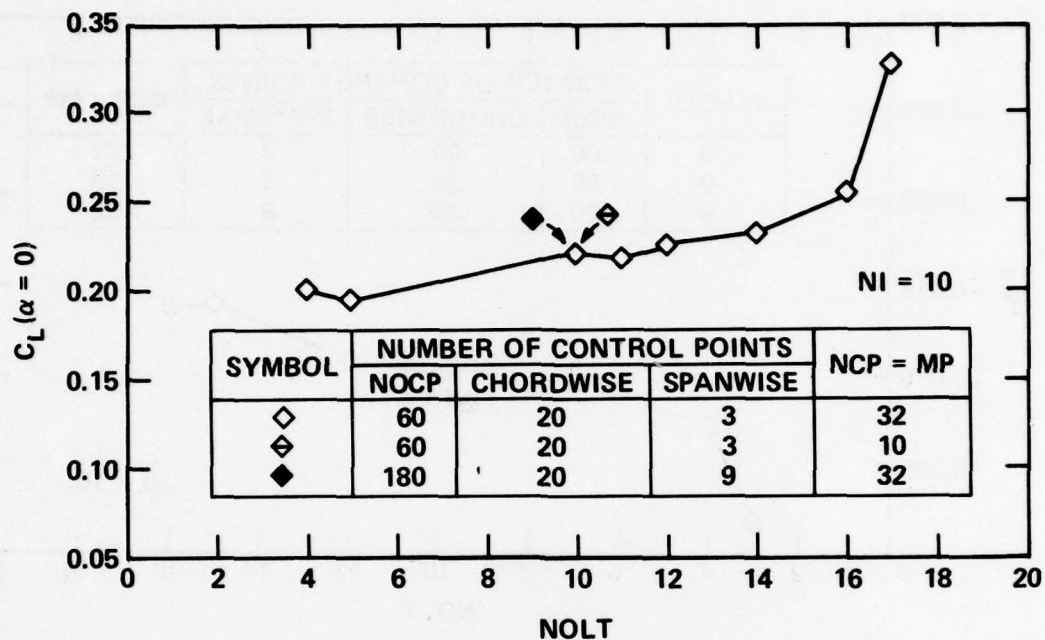


Figure 24 - The Steady Lift Coefficient $C_L(\alpha = 0)$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 6 Hydrofoil at Infinite Depth

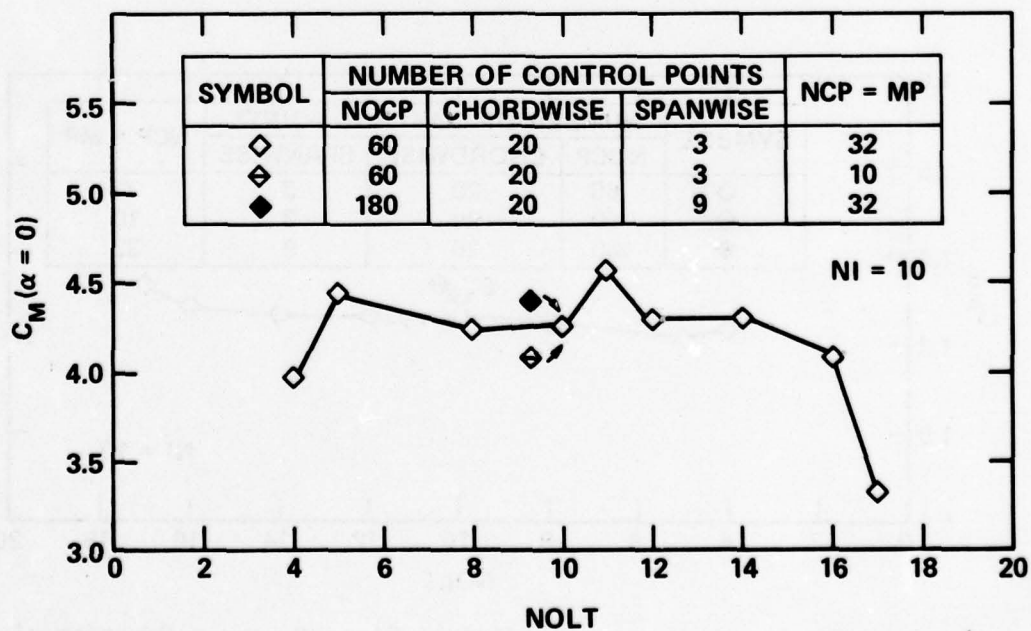


Figure 25 - The Steady Moment Coefficient $C_M(\alpha = 0)$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 6 Hydrofoil at Infinite Depth

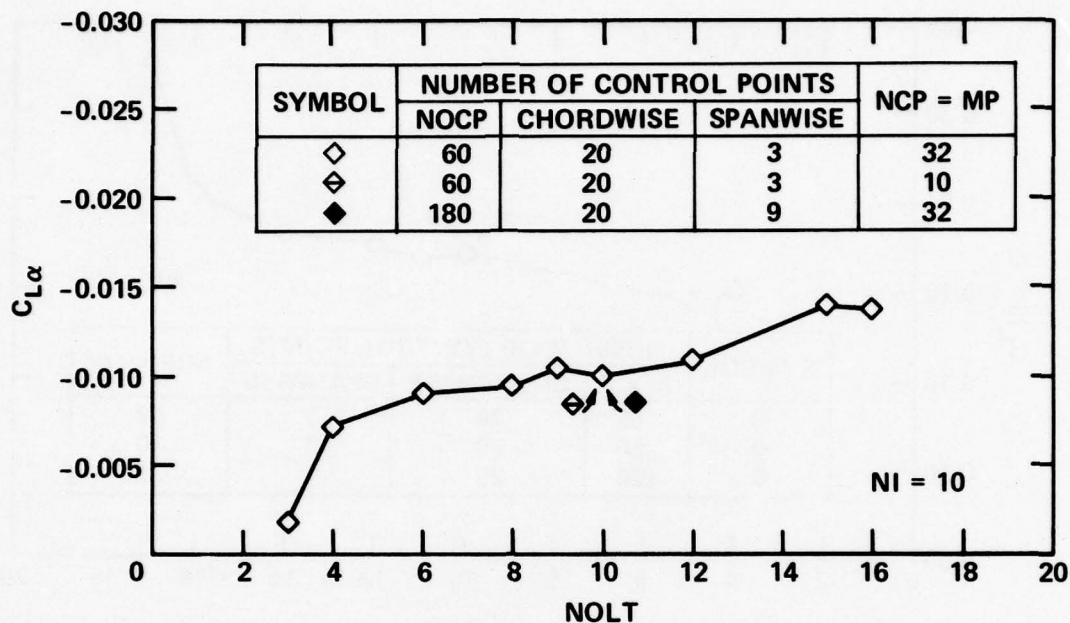


Figure 26 - The Steady Lift Coefficient Slope $C_{L\alpha}$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 6 Hydrofoil at Infinite Depth

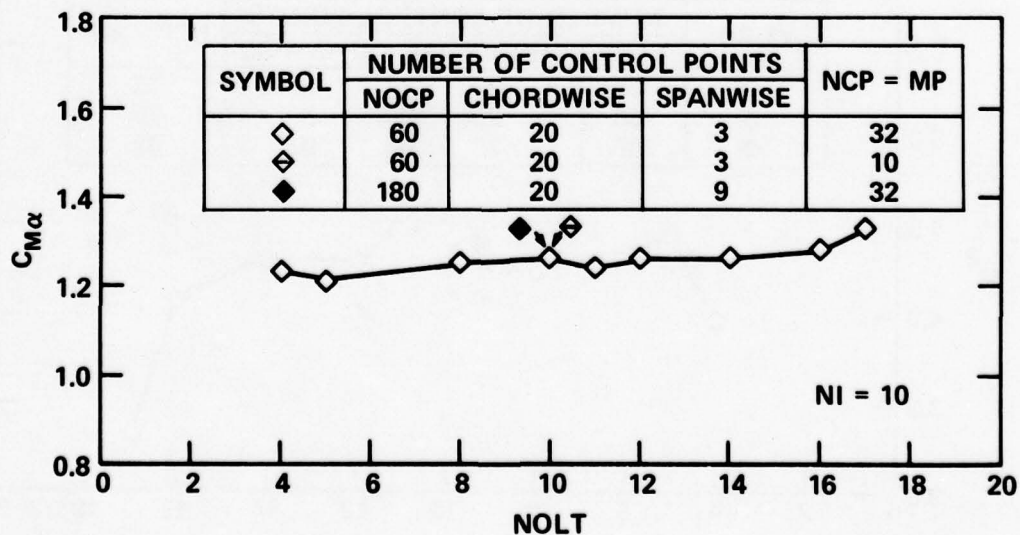


Figure 27 - The Steady Moment Coefficient Slope $C_{M\alpha}$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 6 Hydrofoil at Infinite Depth

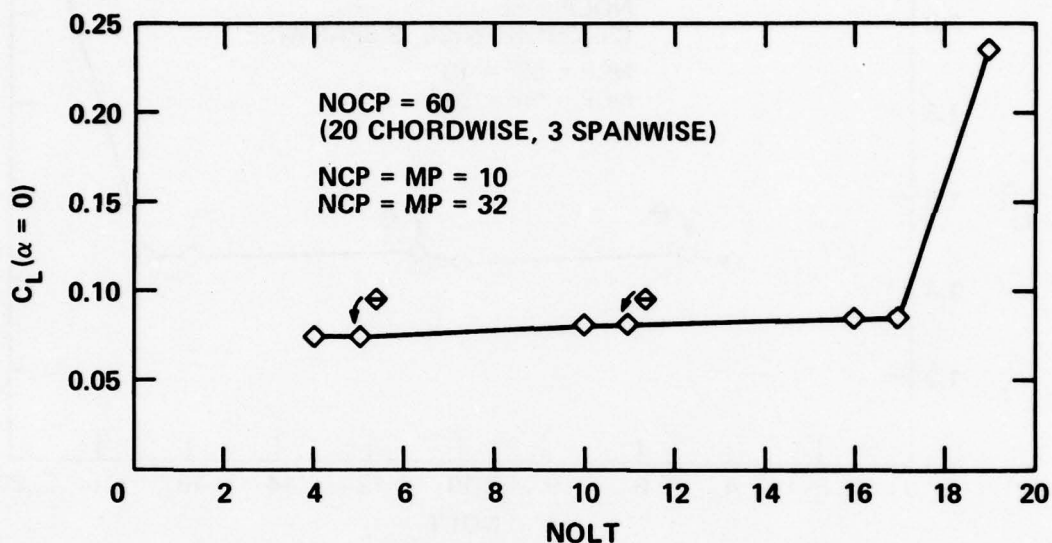


Figure 28 - The Steady Lift Coefficient $C_L(\alpha = 0)$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 1 Hydrofoil at Infinite Depth

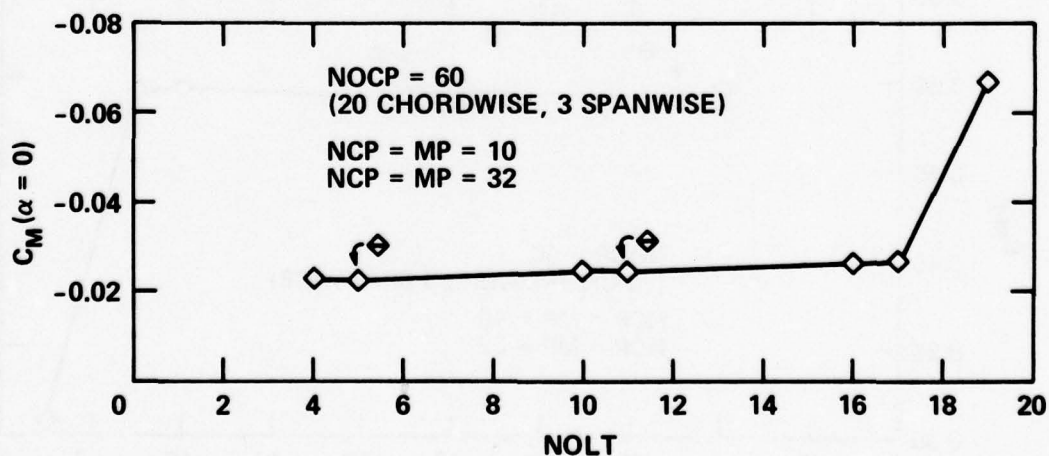


Figure 29 - The Steady Moment Coefficient $C_M(\alpha = 0)$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 1 Hydrofoil at Infinite Depth

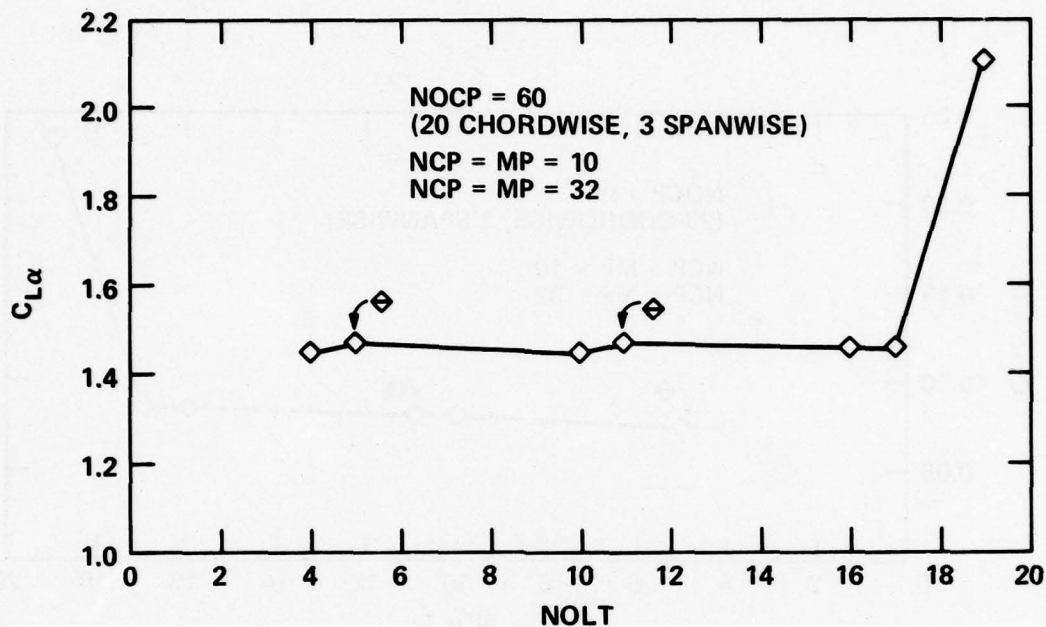


Figure 30 - The Steady Lift Coefficient Slope $C_{L\alpha}$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 1 Hydrofoil at Infinite Depth

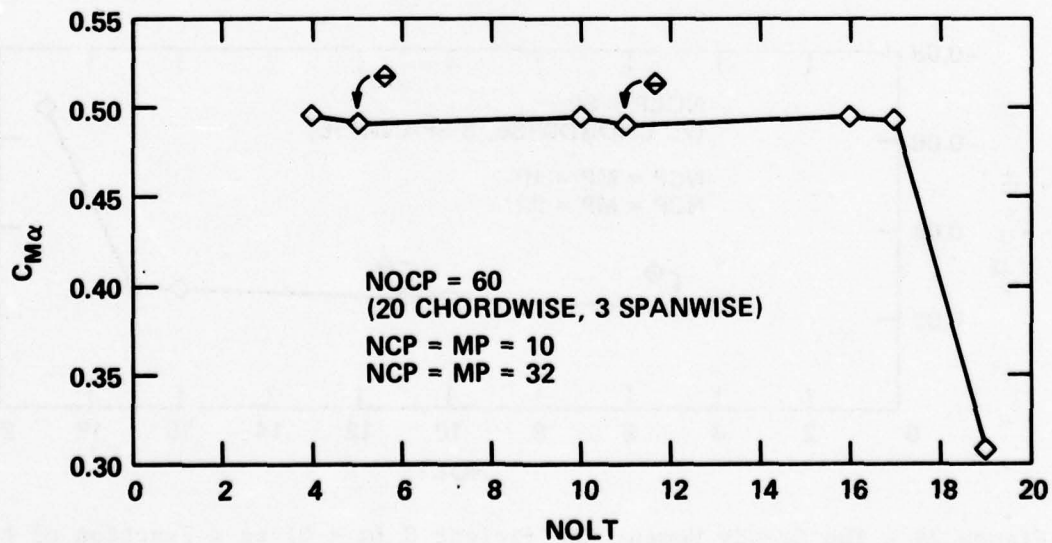


Figure 31 - The Steady Moment Coefficient Slope $C_{M\alpha}$ as a Function of the Number of Chordwise Modes NOLT for a Rectangular AR = 1 Hydrofoil at Infinite Depth

TABLE 4 - EFFECT OF FOIL SUBMERGENCE ON THE NUMERICAL STABILITY OF THE STEADY LOADING CALCULATION

(AR=10 rectangular foil; NACA 16-300 ($a=1.0$) profile; $h/c = 0.2$)

| Parameter | Baseline Value | New Value | Change in Load Coefficient (Percent) | | | |
|--|----------------|-----------|--------------------------------------|---------------|-----------------|---------------|
| | | | $C_L(\alpha=0)$ | $C_{L\alpha}$ | $C_M(\alpha=0)$ | $C_{M\alpha}$ |
| NOCP | 60 | 80 | +3.3 | +5.3 | -6.7 | +2.5 |
| NOLT | 10 | 11 | -1.0 | +3.4 | +6.1 | -6.7 |
| NOST | 2* | 3* | -1.3 | -1.7 | -1.1 | 0.0 |
| NCP=MP | 10 | 32 | +3.2 | -4.8 | +4.3 | -3.3 |
| | 10 | 64 | +3.2 | -4.8 | +4.3 | -3.3 |
| NI | 10 | 32 | 0.0 | 0.0 | 0.0 | 0.0 |
| *NOCP=80, with four spanwise rows of control points. | | | | | | |

TABLE 5 - EFFECT OF SWEEP AND TAPER ON THE NUMERICAL STABILITY OF THE STEADY LOADING CALCULATION

(AR=6.1; $\tau = 0.25$; $\Lambda = 15$ deg; NACA 16-300 ($a=1.0$) streamwise profile; $h/c' = \infty$)

| Parameter | Baseline Value | New Value | Change in Load Coefficient (Percent) | | | |
|--|----------------|-----------|--------------------------------------|---------------|-----------------|---------------|
| | | | $C_L(\alpha=0)$ | $C_{L\alpha}$ | $C_M(\alpha=0)$ | $C_{M\alpha}$ |
| NOCP | 60 | 80 | +2.9 | +3.3 | -5.8 | +6.7 |
| NOLT | 10 | 11 | -1.9 | -6.9 | +2.9 | -2.7 |
| NOST | 2* | 3* | 0.0 | -1.4 | +1.0 | +5.7 |
| NCP=MP | 10 | 32 | 0.0 | -1.1 | +1.0 | +4.7 |
| *NOCP=80, with four spanwise rows of control points. | | | | | | |

variation indicated that the $C_{M\alpha}$ calculation was not stable, and that considerable computer run time would be required to achieve stability. It is concluded that stability of the load coefficients $C_L(\alpha = 0)$, $C_{L\alpha}$, and $C_M(\alpha = 0)$ is not affected by sweep and taper, but that the stability of $C_{M\alpha}$ is greatly reduced.

NUMERICAL STABILITY OF THE UNSTEADY LOADING CALCULATION

In an abbreviated numerical survey, it was found that the unsteady calculation was more sensitive than the steady calculation to the number of spanwise pressure modes used. In other respects, the calculation was similar to the steady loading calculation.

The sensitivity to spanwise pressure modes may have resulted from the choice of the model. An $AR = 10$ rectangular foil was used, with unsteady loading produced by foil oscillation simulating bending and torsional motion. The oscillation amplitudes were symmetrical about the midspan and varied linearly from 0 at the midspan to a maximum at the foil tips. This type of motion produced greater spanwise variation in loading than the constant camber and angle of attack used for the steady loading study. A relatively high reduced frequency of 1.97 was used to accentuate the unsteady aspects of the calculation.

Since preliminary calculations showed a sensitivity to the number of spanwise pressure modes, a baseline array of 15 chordwise and 4 spanwise rows of control points, located as given in Table 6, was used. The magnitudes and phase angles of C_L and C_M were examined for stability; camber lift produces no unsteady component.

As shown in Table 7, the calculated unsteady loading showed good stability when numerical parameters were varied from the baseline values. The requirement for 4 spanwise rows of control points is evident in Figure 32. Stability breakdown again occurred at high values of $NOLT$, as shown in Figure 33. Except for the rearrangement in control point location and the addition of a pressure mode in the spanwise direction, the numerical parameter values selected for the unsteady calculation were the same as for the steady calculation. The values chosen are given in Table 6.

SUMMARY OF RESIDUAL INSTABILITY

Both steady and unsteady loading calculations failed to achieve a value which was stable to several significant figures. Estimating residual instability with a high degree of confidence is not possible, because most

TABLE 6 - INPUT PARAMETER BASELINE VALUES REQUIRED
FOR APPROXIMATE NUMERICAL STABILITY OF
THE UNSTEADY LOADING CALCULATION

| Program Variable | Input Value |
|------------------|---|
| NOCP | 60 |
| NOLT | 10 |
| NOST | 3 |
| NCP | 10 |
| MP | 10 |
| NI | 10 |
| XOC | 0.025,0.05,0.1,0.15,0.25,0.3,0.4,0.45,0.55, 0.6,0.7,0.75,0.85,0.95,0.975 |
| SOS | 0.1,0.35,0.65,0.9 |

TABLE 7 - NUMERICAL STABILITY OF THE UNSTEADY LOADING CALCULATION
(AR=10 rectangular foil; uncambered profile; $h/c = \infty$; bending and
torsional oscillation)

| Parameter | Baseline Value | New Value | Oscillation Mode | Change in Load Coefficient | | | |
|---|----------------|-----------|------------------|----------------------------|-----------------|--------------------|-----------------|
| | | | | C_L (percent) | ϕ (deg) | C_M (percent) | ϕ (deg) |
| NOCP | 60 | 80 | Bending | 0 | 0 | 0 | 0 |
| | 60 | 80 | Torsion | 0 | +1 | -1 | 0 |
| NOST | 3* | 4* | Bending | 0 | 0 | +1 | 0 |
| NCP=MP | 10 | 32 | Bending | +1 | +1 | +4 | 0 |
| | 10 | 32 | Torsion | 0 | +1 | +1 | +1 |
| NI | 10 | 32 | Bending | 0 | 0 | 0 | 0 |
| | 10 | 32 | Torsion | 0 | 0 | 0 | 0 |
| *NOCP=75, with 5 spanwise rows of control points. | | | | | | | |

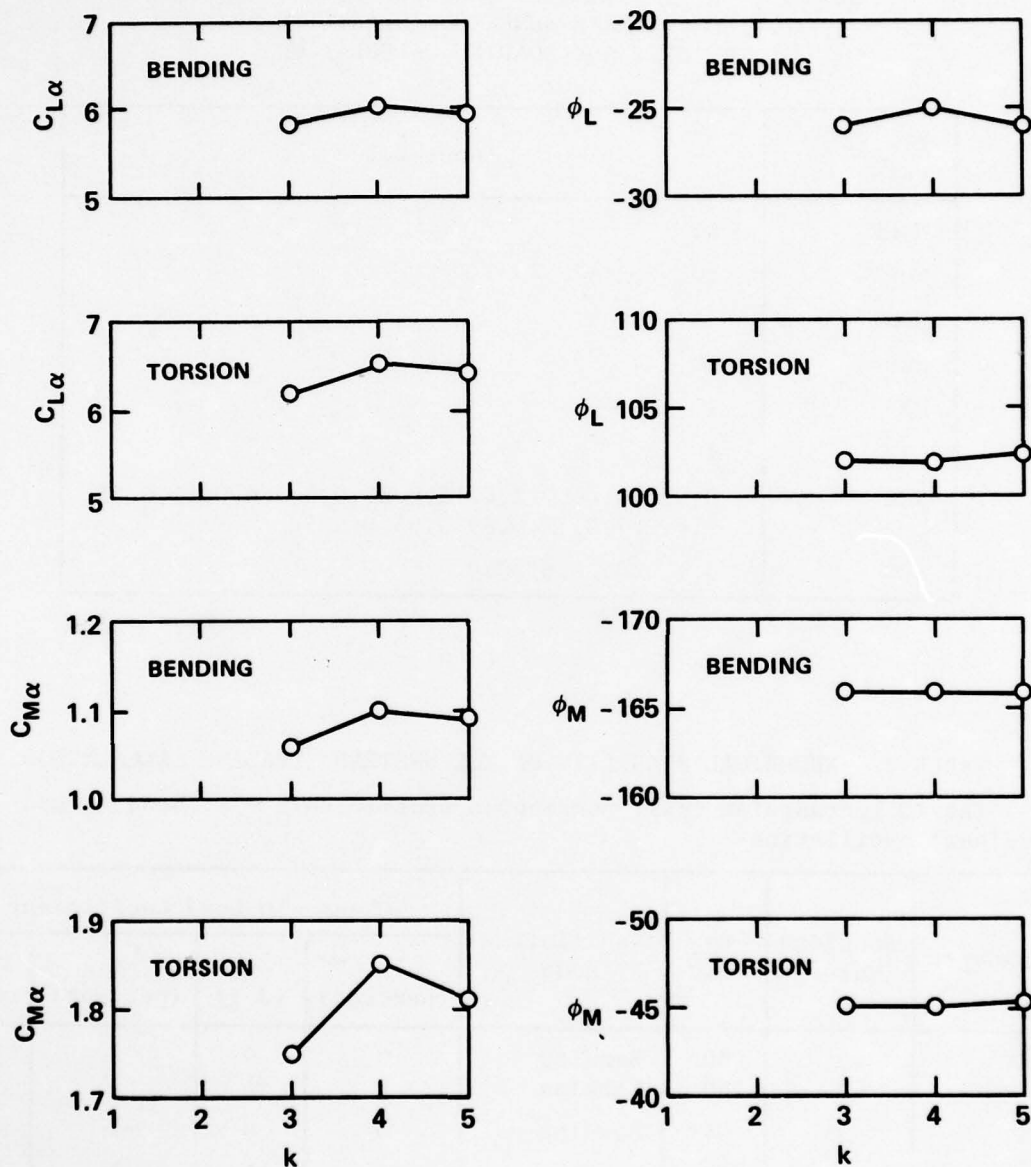


Figure 32 - The Effect of the Number of Spanwise Control Points k on the Lift Coefficient Magnitude $|C_{L\alpha}|$ and Phase ϕ_L and Moment Coefficient Magnitude $|C_{M\alpha}|$ and Phase ϕ_M for Bending and Torsion Oscillations for a Rectangular $AR = 10$ Hydrofoil at Infinite Depth with $k = 1.97$ (Number of Chordwise Control Points = 15; $NOCP = 15 * k$)

Figure 33 - The Effect of the Number of Chordwise Modes NOLT on the Unsteady Loading due to Bending and Torsional Oscillations of a Rectangular AR = 10 Hydrofoil at Infinite Depth with $k = 1.97$ (NOCP = 60; 15 Chordwise, 4 Spanwise)

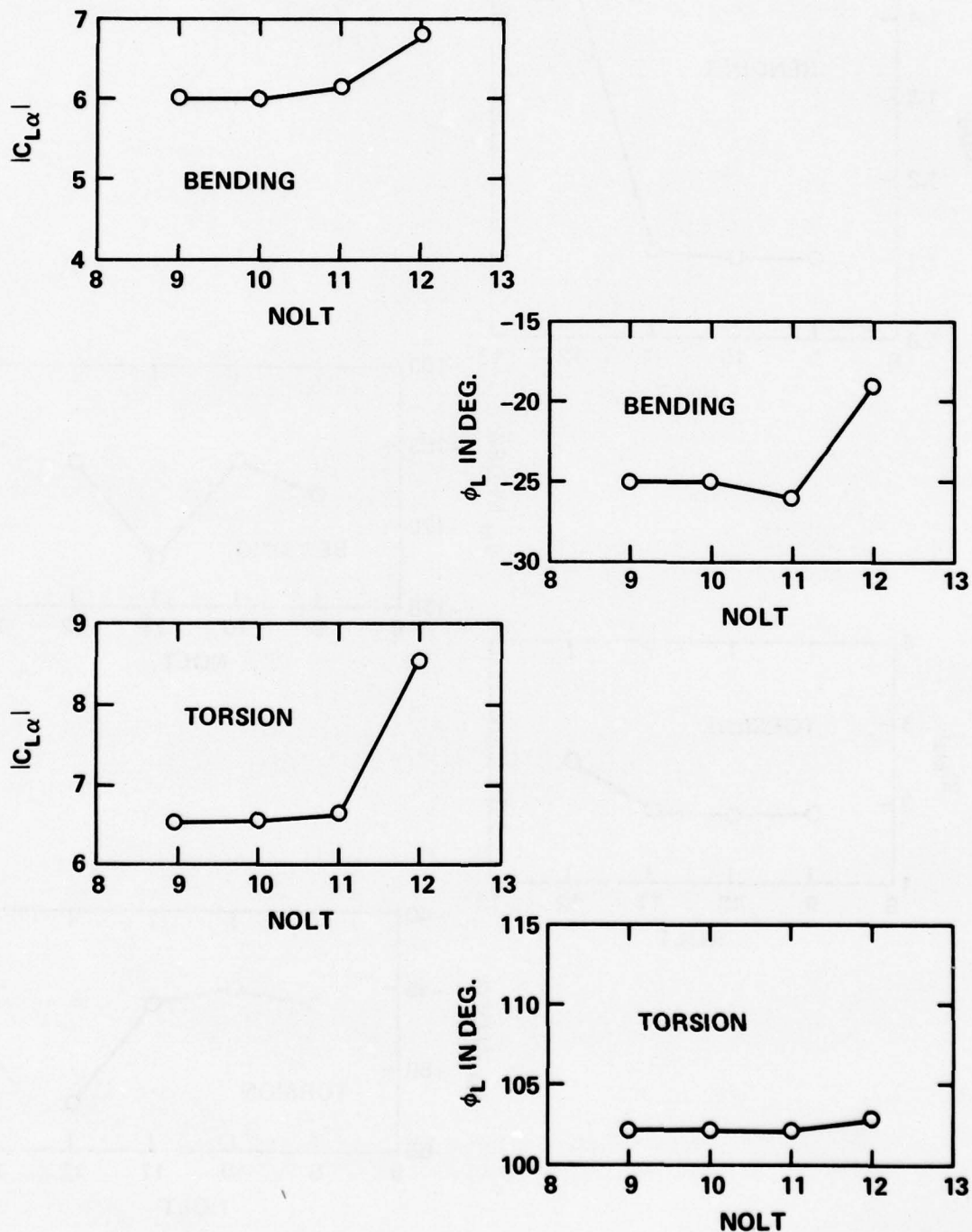


Figure 33a - Lift Coefficient Magnitude $|C_{L\alpha}|$ and Phase Angle ϕ_L

Figure 33 (Continued)

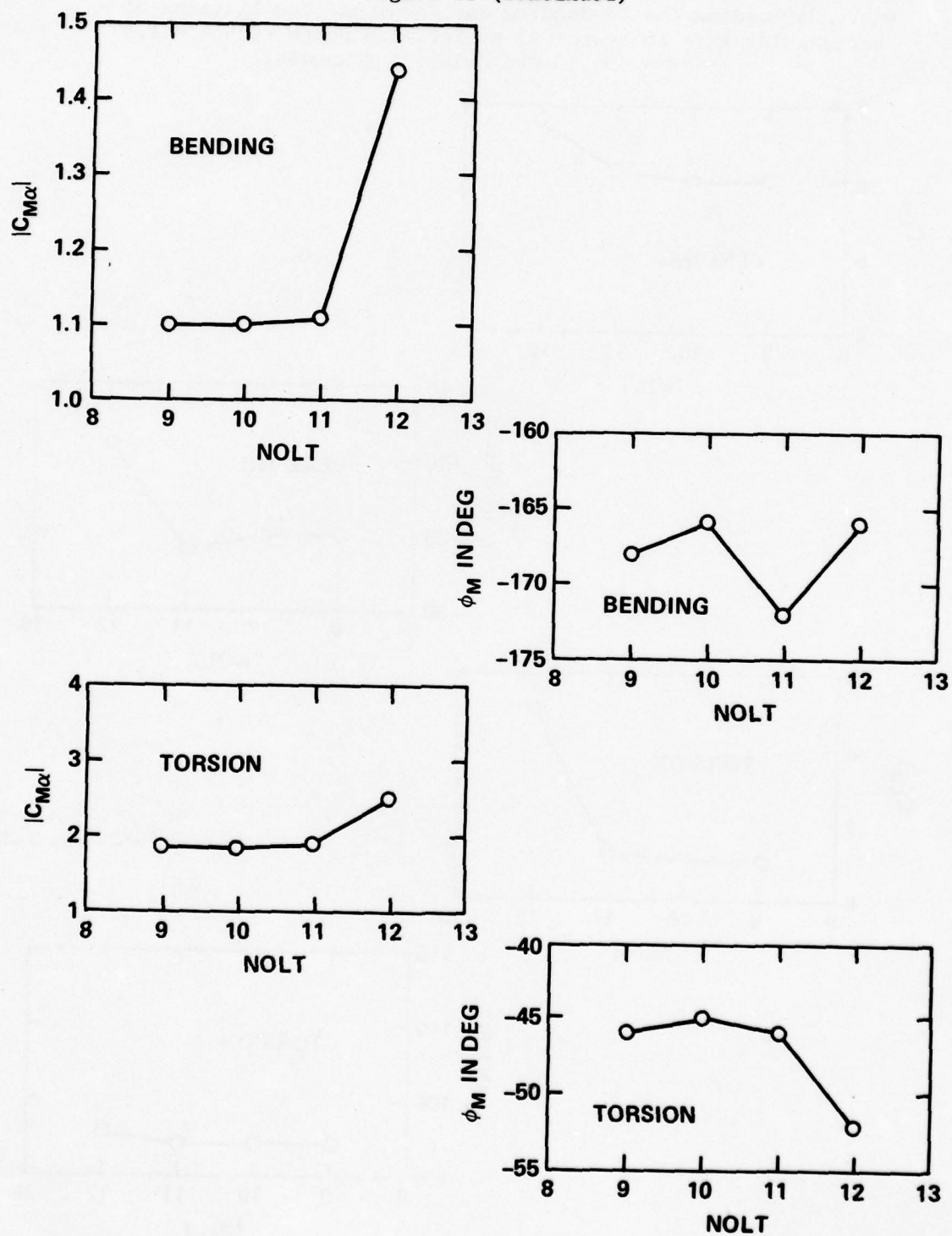


Figure 33b - Moment Coefficient Magnitude $|C_{M\alpha}|$ and Phase Angle ϕ_M

calculated results oscillated around a changing local average, rather than oscillating around or asymptotically approaching a constant limiting value. Attaining stability may require much smaller numerical intervals, which were not attempted for cost reasons, or may be limited to chordwise loading distributions which are easily represented by trigonometric modes.

To provide a rough approximation of the residual instability, the incremental change in load coefficient, due to an increase in the number of chordwise pressure modes (NOLT) from 10 to 11, was used. The instabilities thus determined are given in Table 8.

COMPUTATIONAL PRECISION

The Widnall program was used on three different computers: the IBM 7090 and CDC 6700 computers at the Center, and an IBM 360 computer at the Johns Hopkins University Applied Physics Laboratory (APL). It was surprising to discover that initially the program yielded substantially different results on the different computers although it was written in the same language (FORTRAN IV). These preliminary calculations were done in single precision (approximately eight significant figures) except for the matrix inversion which was done in double precision. Line-by-line comparisons of intermediate program steps revealed the following reason for the discrepancies. The computations of the matrix elements relating the pressure coefficients to the downwash involve differences of terms of similar magnitude. In some cases, the differences were formed from meaningless, computer-generated digits carried at the low end of the terms being subtracted. It was found that these imprecise quantities were associated with high order chordwise pressure modes, which are insignificant in comparison with modes of low order. Unfortunately, however, these erroneous numbers tended to cluster in rows and columns of the calculated matrix. Consequently, the determinant of the matrix was erroneous, and so was the calculated pressure distribution.

As an example of the effect of computer system characteristics in such circumstances, the APL IBM 360 used two different system control tapes which gave differing values for corresponding matrix elements for the

TABLE 8 - APPROXIMATE NUMERICAL INSTABILITIES FOR STEADY AND UNSTEADY LOADING COEFFICIENTS

| Type of Loading | Foil Configuration | Instability (Percent) | | | |
|-----------------|---|-----------------------|---------------|-----------------|---------------|
| | | $C_L(\alpha=0)$ | $C_{L\alpha}$ | $C_M(\alpha=0)$ | $C_{M\alpha}$ |
| Steady | AR=10, rectangular | 1 | 8 | 9 | 9 |
| | AR=6, rectangular | 2 | 4 | 5 | 4 |
| | AR=1, rectangular | 1 | 1 | 1 | 1 |
| | AR=6.1, swept and tapered | 2 | 7 | 3 | 27 |
| Unsteady | AR=10, rectangular, bending and torsion | - | 3 | - | 3 |

single precision version of the program. With the use of double precision values (12 precise digits) for all of the program variables and constants, the two systems gave identical results. In fact, the results also agreed with those from the IBM 7090 computer using double precision (16 precise digits) and with those from the CDC 6700 (15 precise digits).

No effort was made to determine the relationships between the number of chordwise modes and the required number of precise digits. However, all of the steady and unsteady calculations presented in this report were performed using 15 precise digits and the Center's CDC 6700.

The discovery that the pressure distribution calculated by the computer program might have been imprecise caused concern for the validity of the constants used in the program. An examination of the unsteady program, which contained more constants than did the steady program, revealed no more than a 1-percent change in the calculated lift and moment coefficients when the least significant figure in each of the constants was randomly changed by one unit. Therefore, it was concluded that the program constants were valid and did not need more significant figures.

COMPARISON WITH EXPERIMENT

To determine the accuracy of the Widnall calculation in predicting hydrofoil loading, loading values were calculated for a large number of

small-scale hydrofoil models for which experimental data were available. Both steady and unsteady loading conditions were represented in these test cases. In addition, because only a small amount of data was available for unsteady loading on hydrofoils, the unsteady hydrofoil data were supplemented by a limited amount of unsteady data obtained from airfoil models. With regard to the theory, additional perspective was provided by parallel calculations made with other theoretical approaches. In the case of a lifting-surface theory, programmed by Bandler⁶ from an original development by Richardson,⁷ these calculations were made by the authors. Other calculated theoretical values were reproduced from previous publications.

Only very simple types of hydrofoil and airfoil configurations were examined to minimize demands on the theories. All hydrofoils consisted of a planar lifting surface traveling in a horizontal orientation at varying depths beneath a free surface, or extended perpendicularly to a large end plate. The airfoils were similarly extended from a large wall. The foils were either actually or effectively bilaterally symmetrical. Both rectangular and swept, tapered planforms were included. Most models had supporting struts, and one had a fairing (pod) at the strut-foil junction. In such cases, the foil was considered, in the theoretical representation, to include the area within the strut and pod formed by extending the leading and trailing edges of the foil. No corrections were made for effects of the strut and pod on the predicted foil loading.

STEADY LOADING--THEORY AND EXPERIMENT

Calculated hydrodynamic loading due to steady motion was compared with data from twenty-one different hydrofoil model configurations and one airfoil model. The models⁸⁻²¹ are described in Appendix A. Two models corresponded to foil systems on U.S. Navy hydrofoil craft; the others covered a wide range of characteristics. Both measured and predicted loading values are shown in Figures 34 through 40. Ranges of experimental uncertainty are given when available from the data source. The large uncertainties in lift at zero incidence will be commented on shortly. In this study, experimental uncertainty refers to the estimated maximum range of error between the measured value and the actual value.

Figure 34 - Total Steady Lift Coefficient as a Function of Submergence for Various Hydrofoils with Rectangular Planforms ($\Lambda = 0$; $\tau = 1.0$)

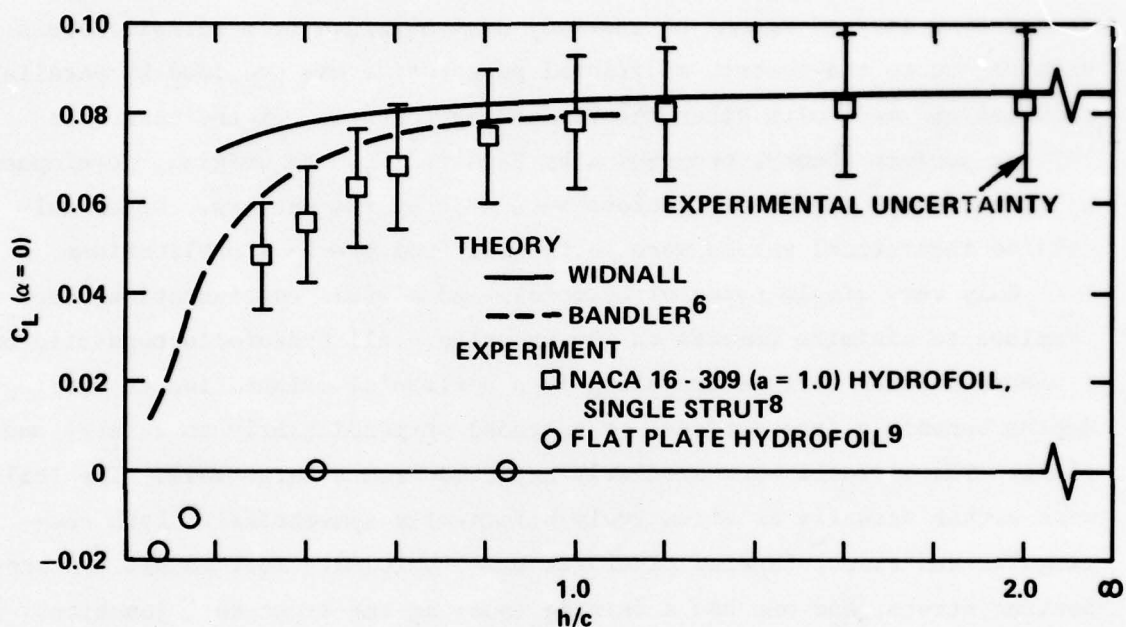


Figure 34a - $AR = 1$

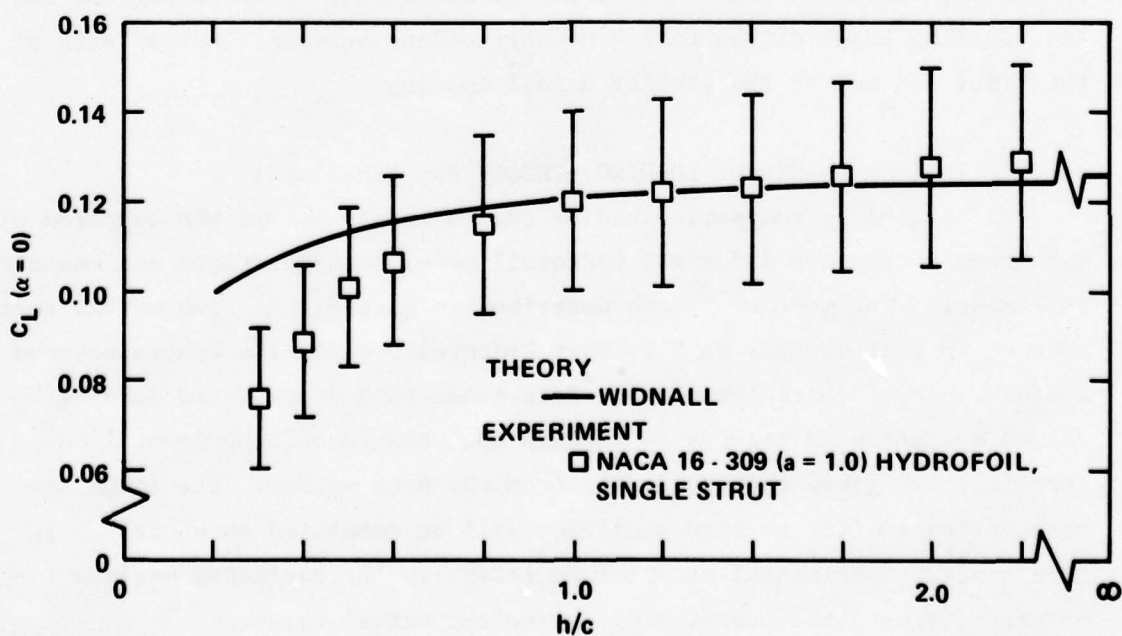


Figure 34b - $AR = 2$

Figure 34 (Continued)

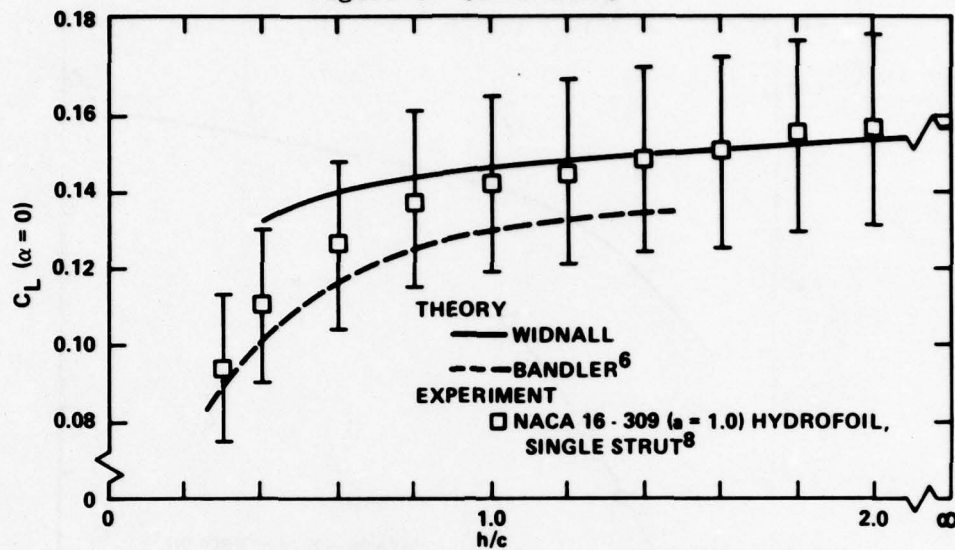


Figure 34c - $AR = 3$

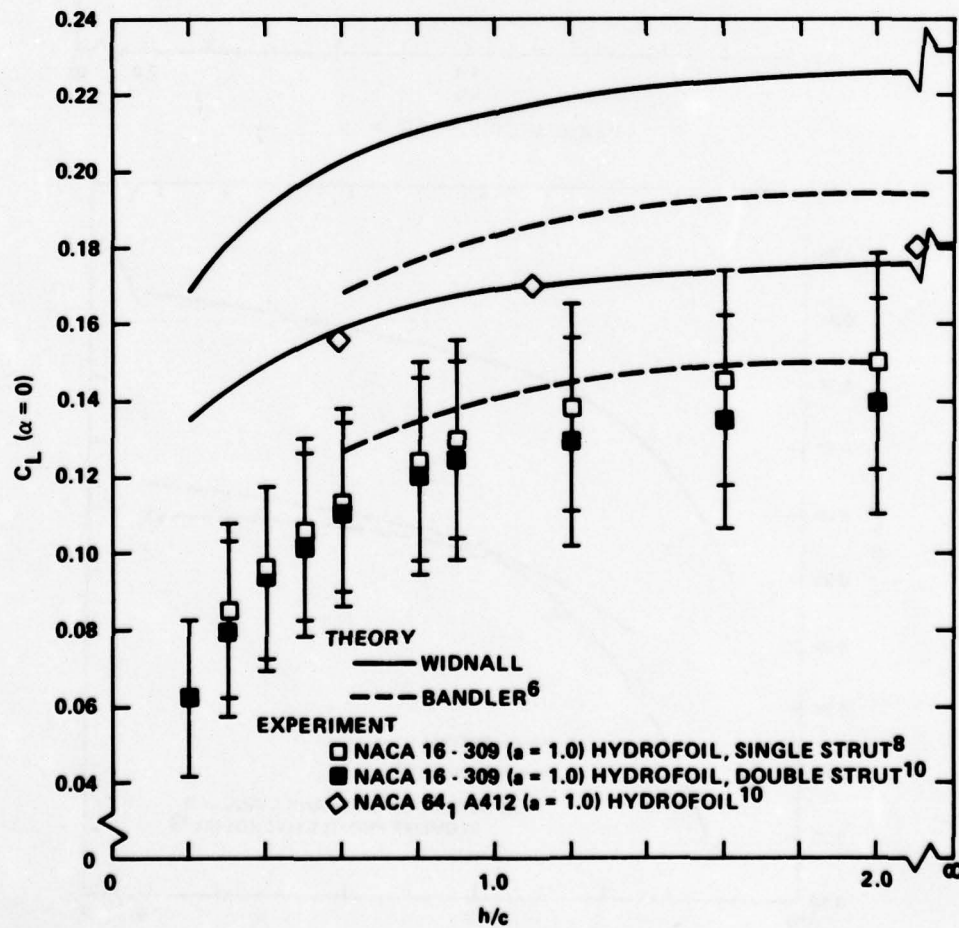


Figure 34d - $AR = 4$

Figure 34 (Continued)

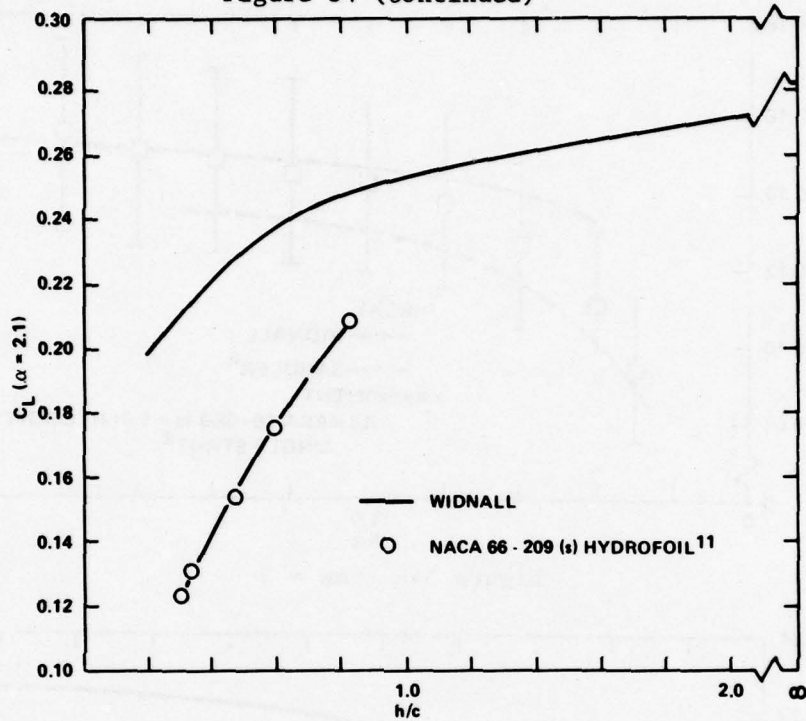


Figure 34e - AR = 5

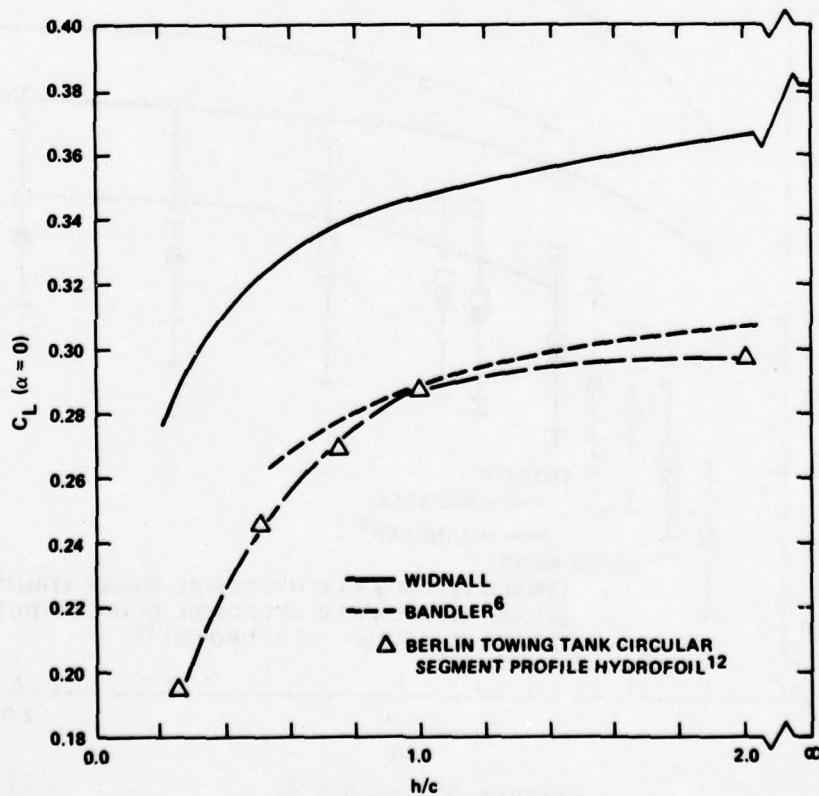


Figure 34f - AR = 5.84

Figure 34 (Continued)

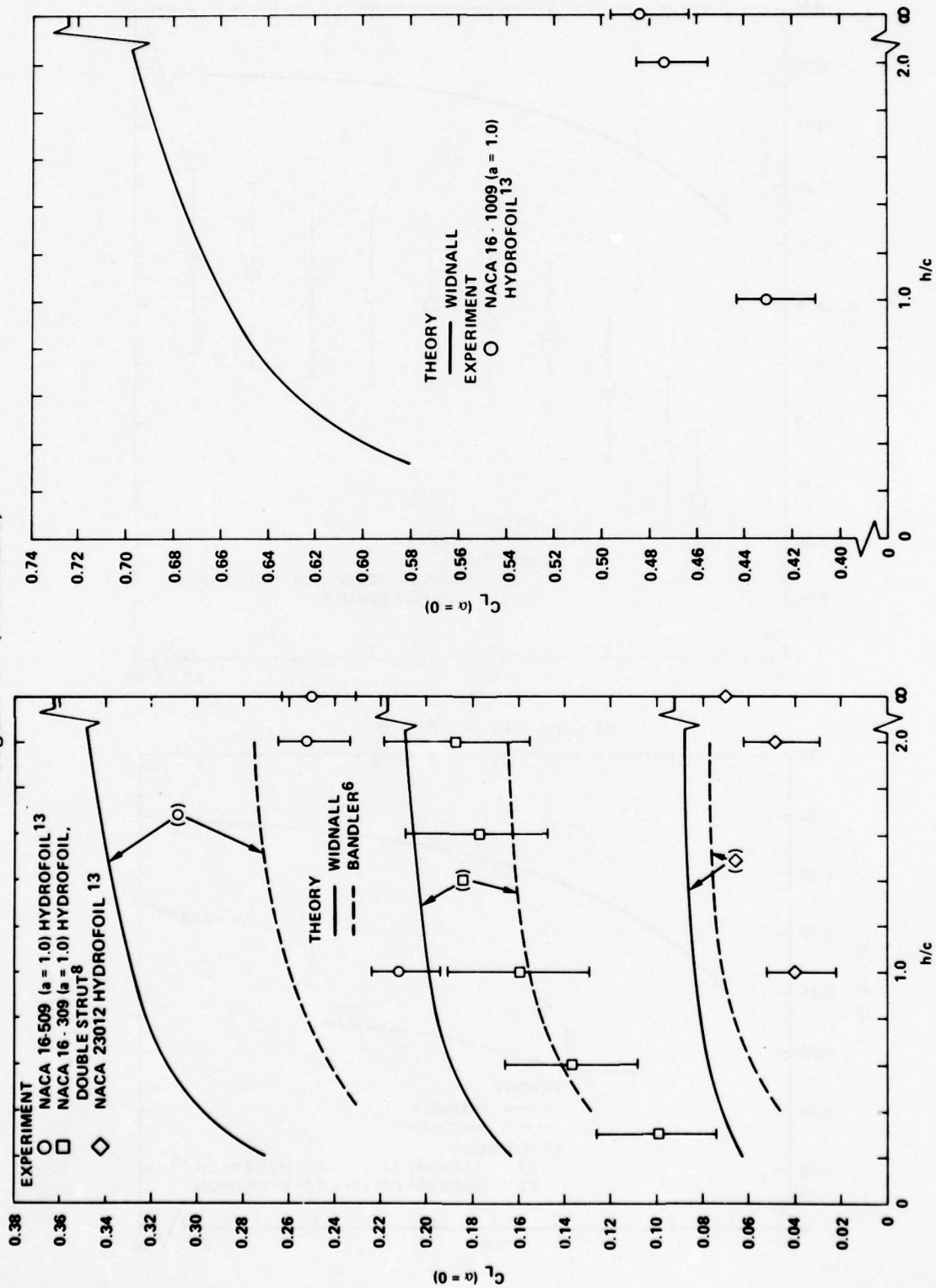


Figure 34g - AR = 6

Figure 34 (Continued)

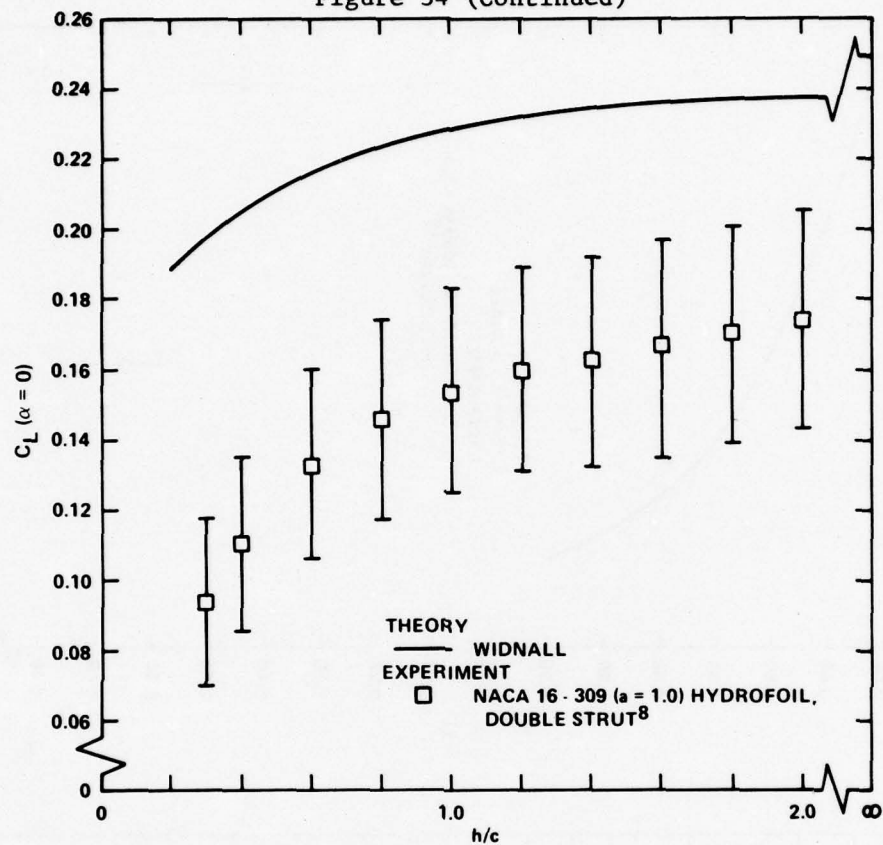


Figure 34h - AR = 8

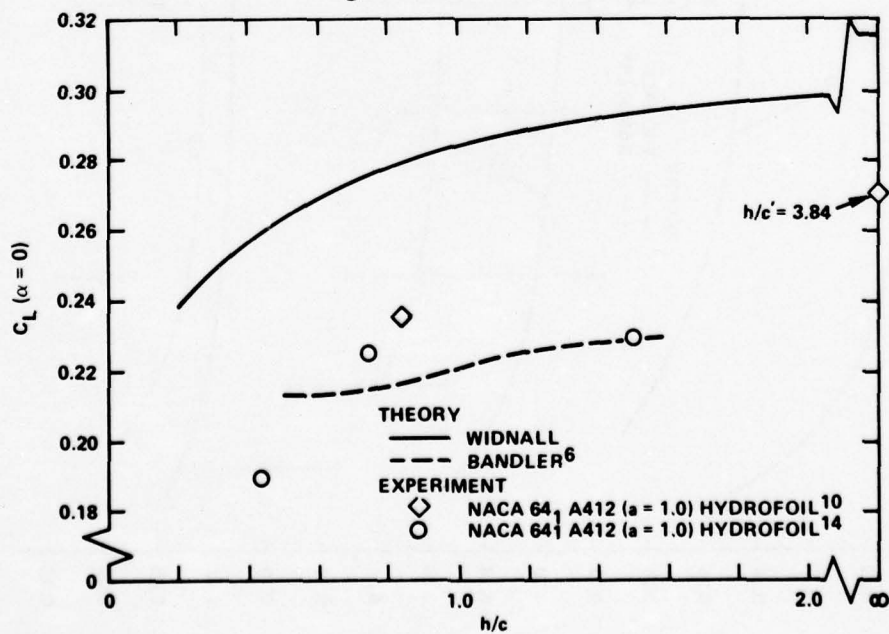


Figure 34i - AR = 10

Figure 35 - Total Steady Lift Slope Coefficient as a Function of Submergence for Various Hydrofoils with Rectangular Planforms
($\Lambda = 0$; $\tau = 1.0$)

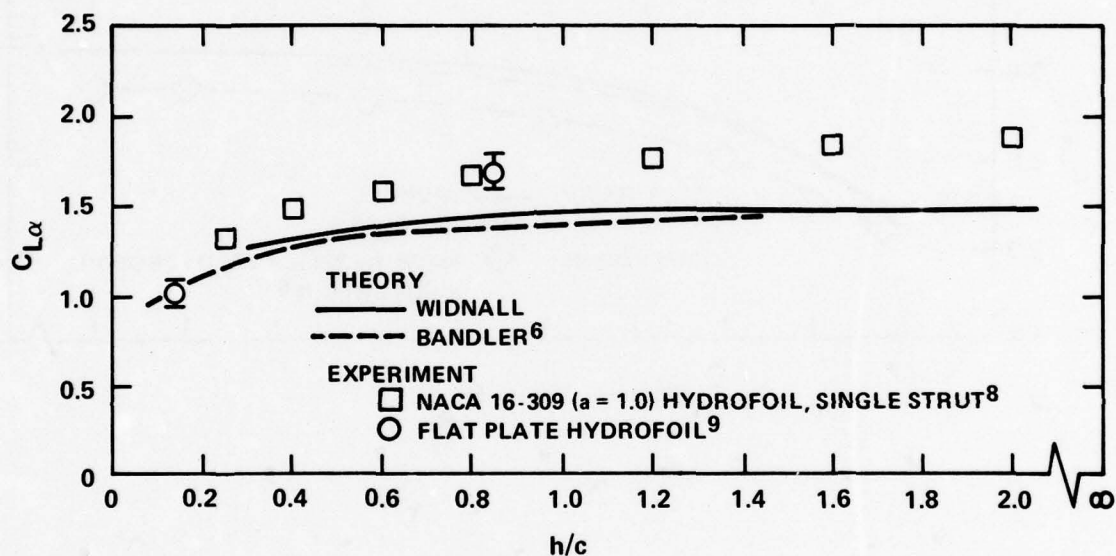


Figure 35a - $AR = 1$

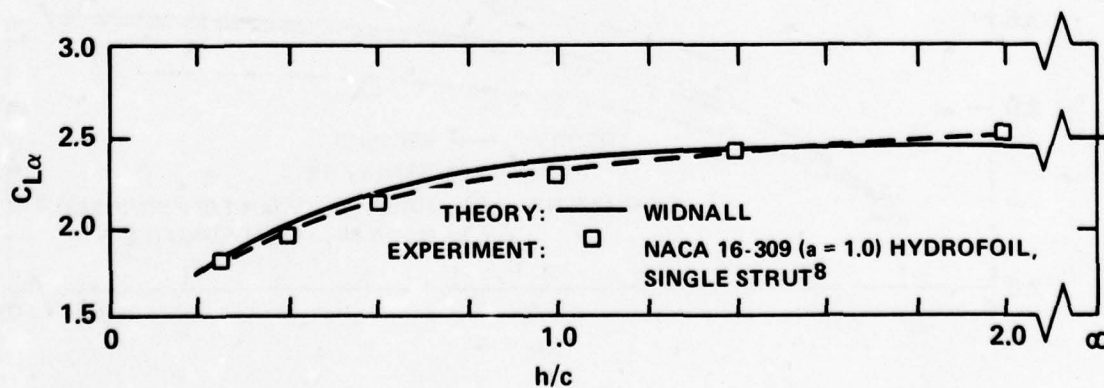


Figure 35b - $AR = 2$

Figure 35 (Continued)

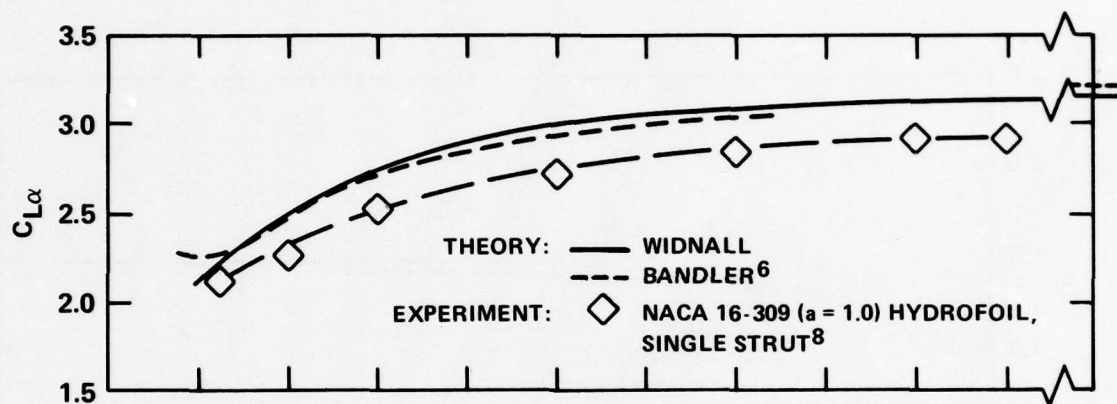


Figure 35c - $AR = 3$

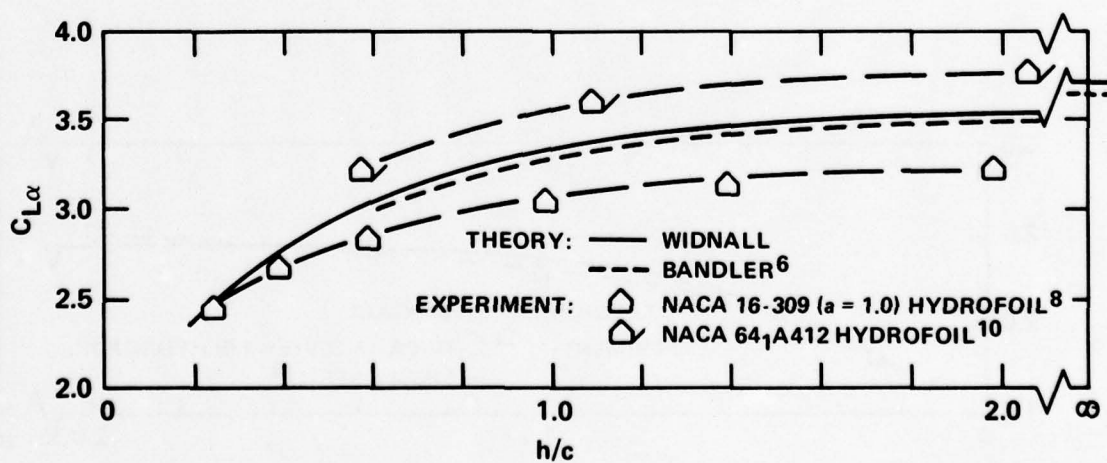


Figure 35d - $AR = 4$

Figure 35 (Continued)

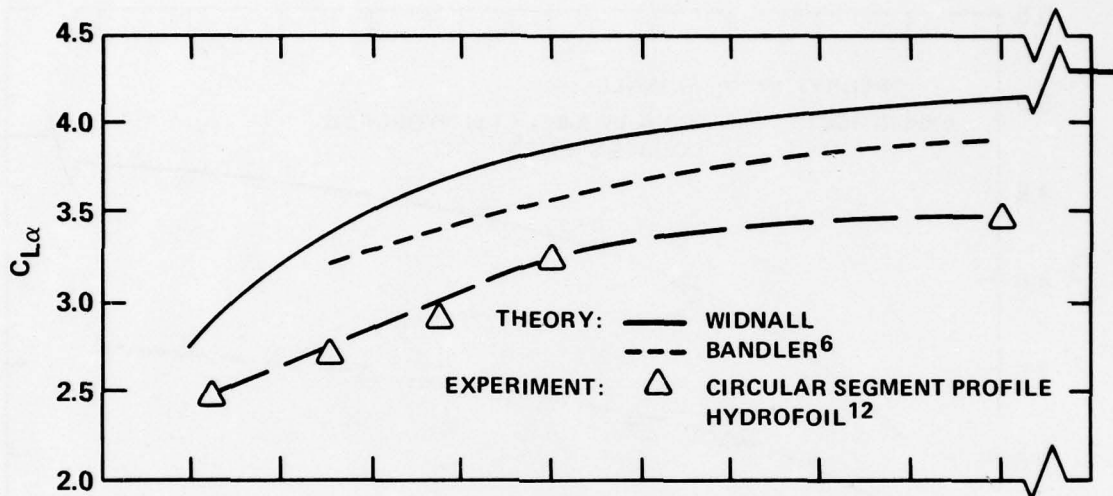


Figure 35e - AR = 5.84

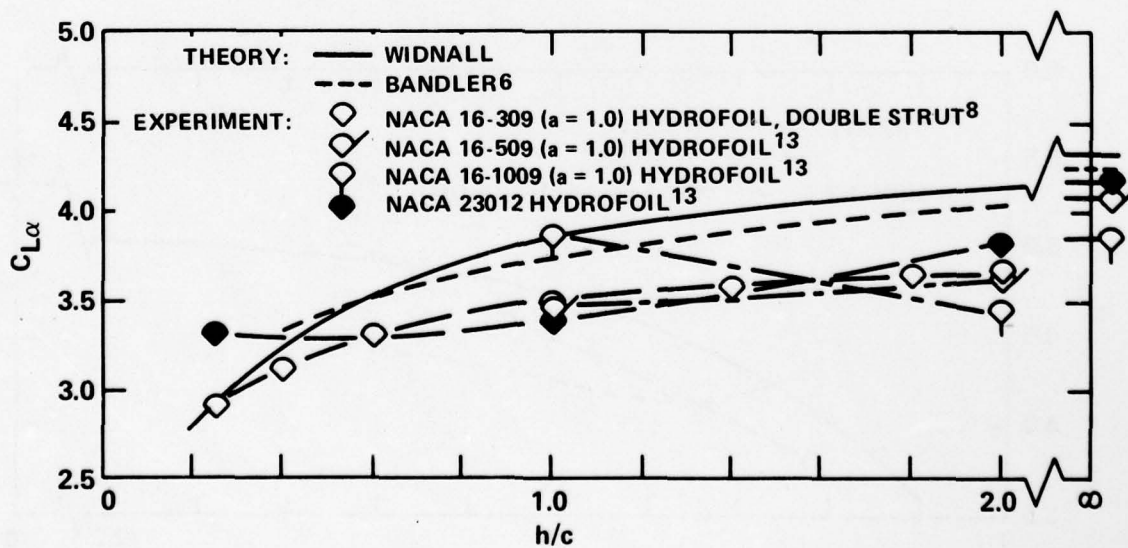


Figure 35f - AR = 6

Figure 35 (Continued)

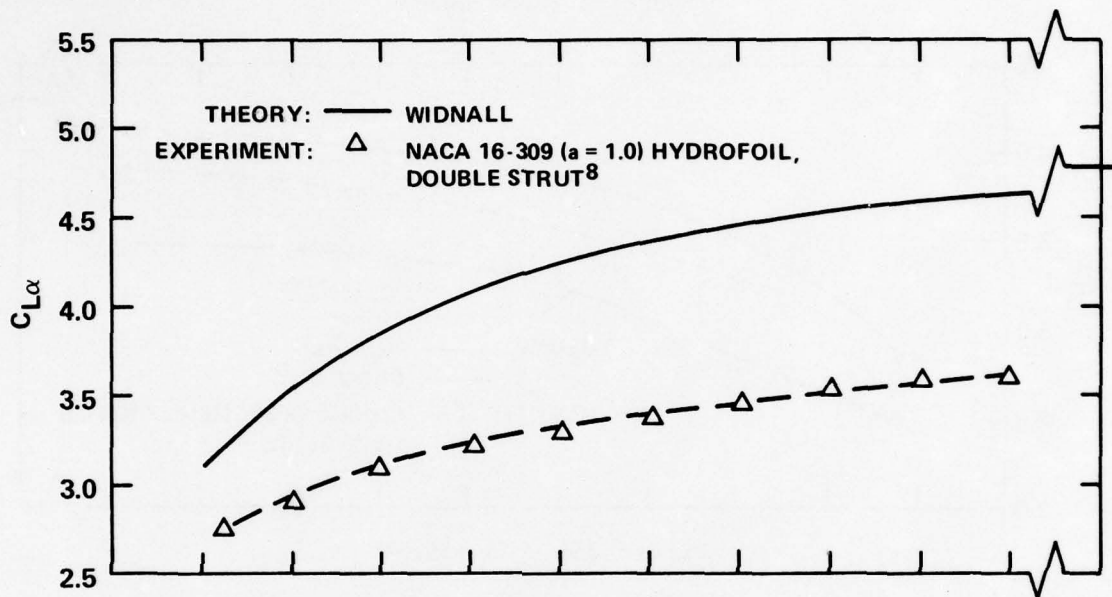


Figure 35g - AR = 8

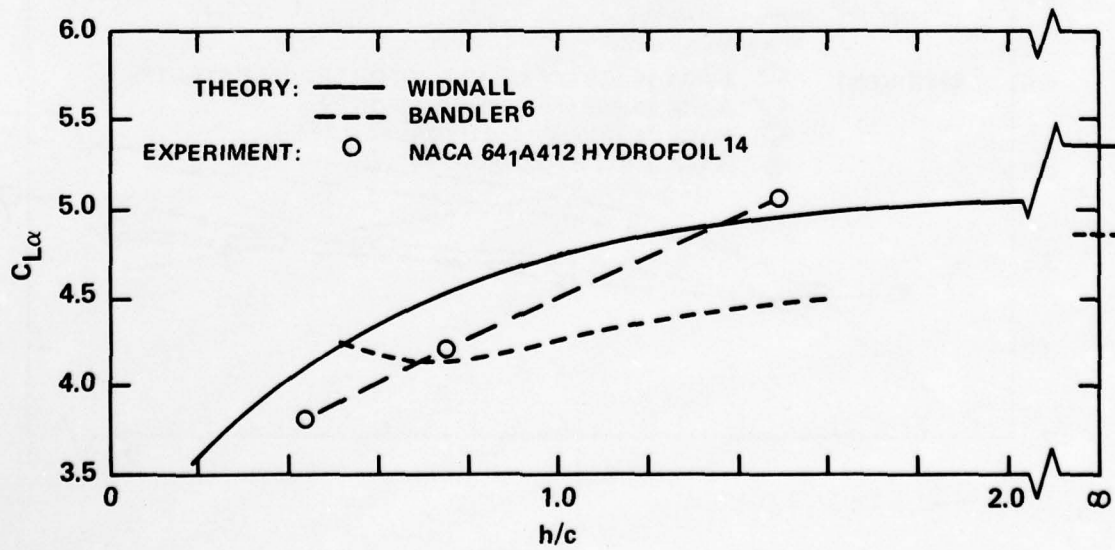


Figure 35h - AR = 10

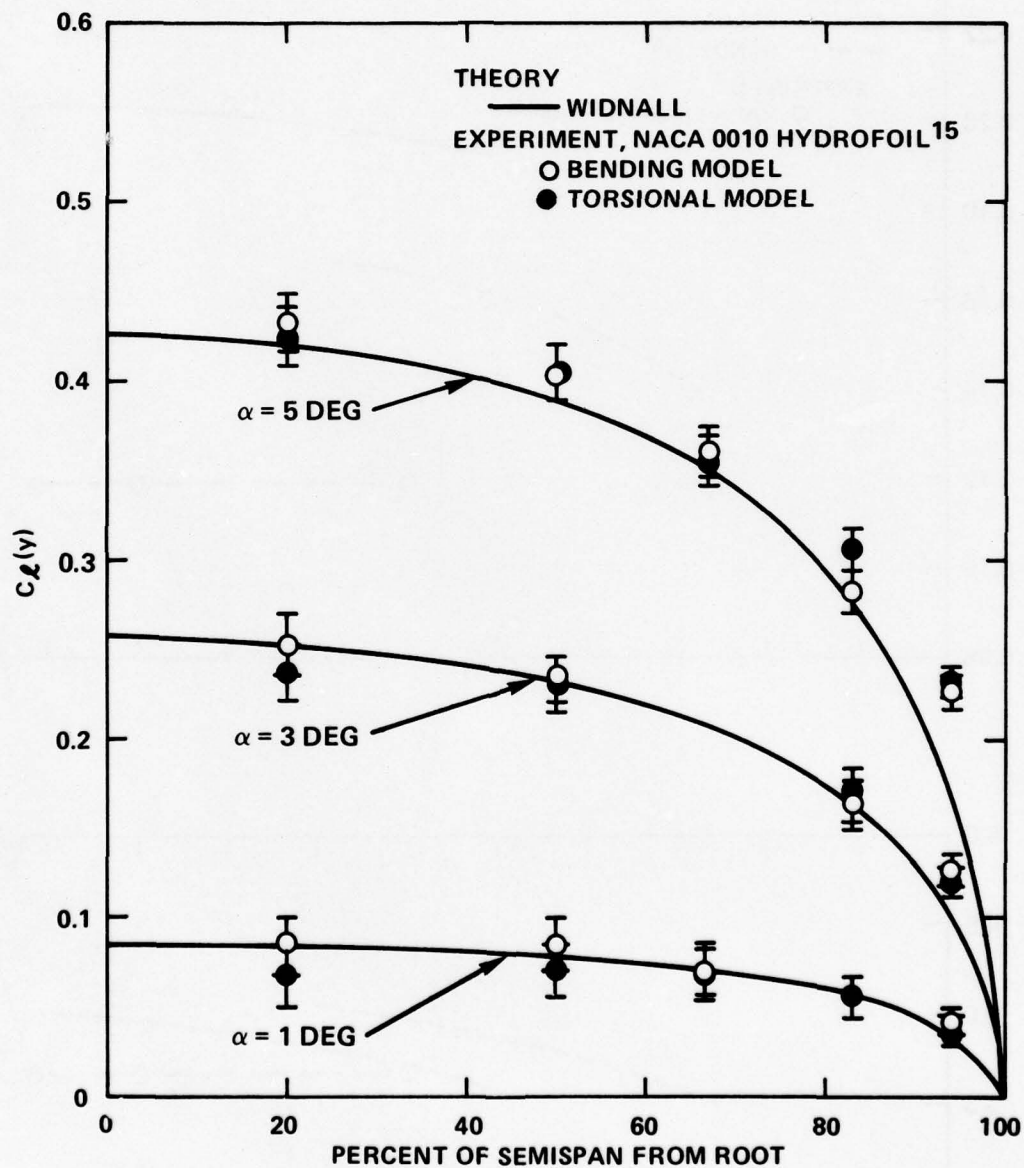


Figure 36 - Spanwise Distribution of Steady Lift Coefficient for the NACA 0010 Hydrofoil ($\Lambda = 0$; $\tau = 1.0$; $AR = 5$)

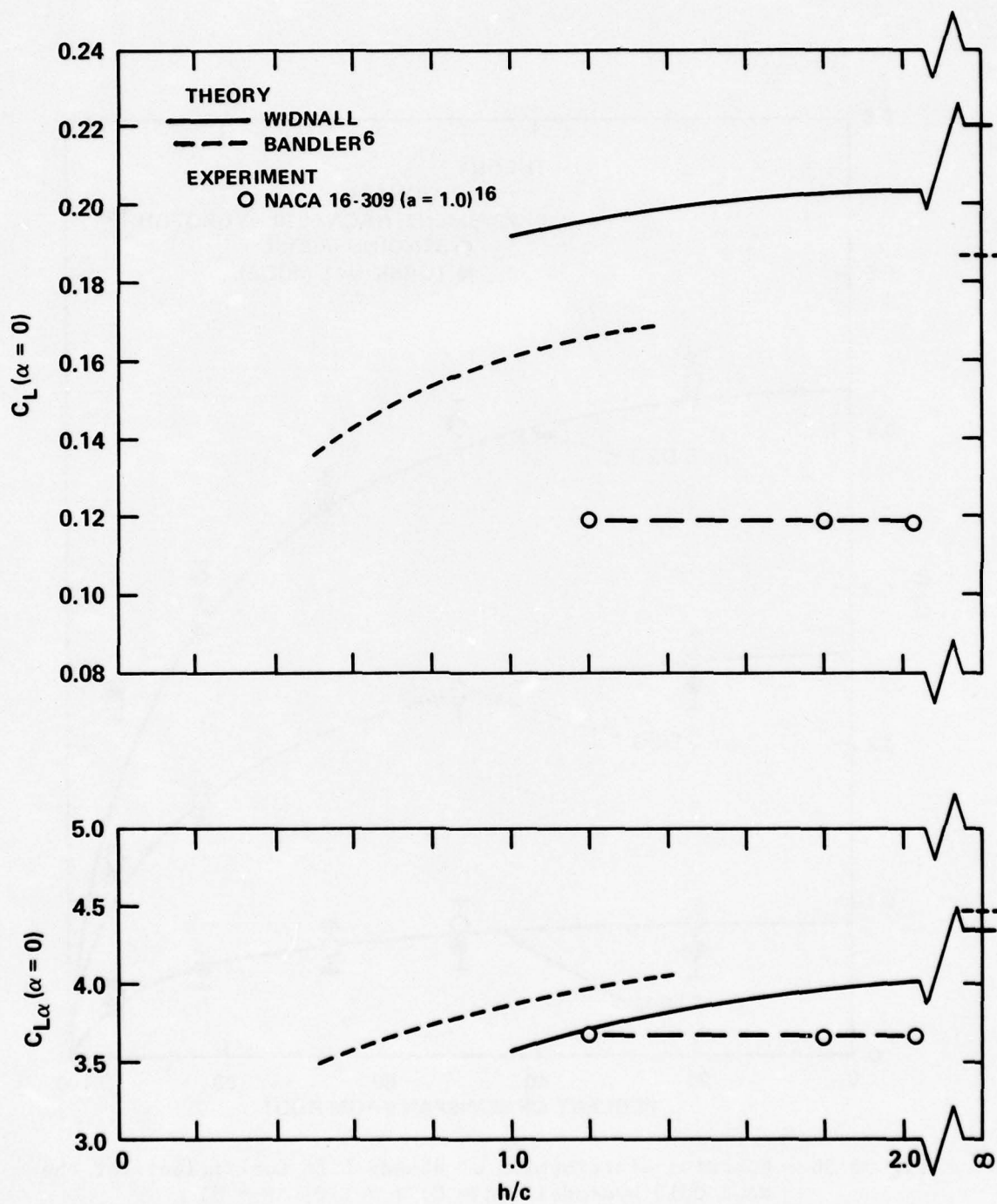


Figure 37 - Total Steady Lift and Lift Slope Coefficients as Functions of Submergence for the One-Eighth-Scale PCH-1 Hydrofoil Model ($\Lambda = 15$ Degrees; $\tau = 0.25$; $AR = 6.1$)

Figure 38 - Total Steady Loading as a Function of Submergence for the
One-Twelfth-Scale AGEH-1 Hydrofoil Model
($\Lambda = 35$ Degrees; $\tau = 0.3$; AR = 3)

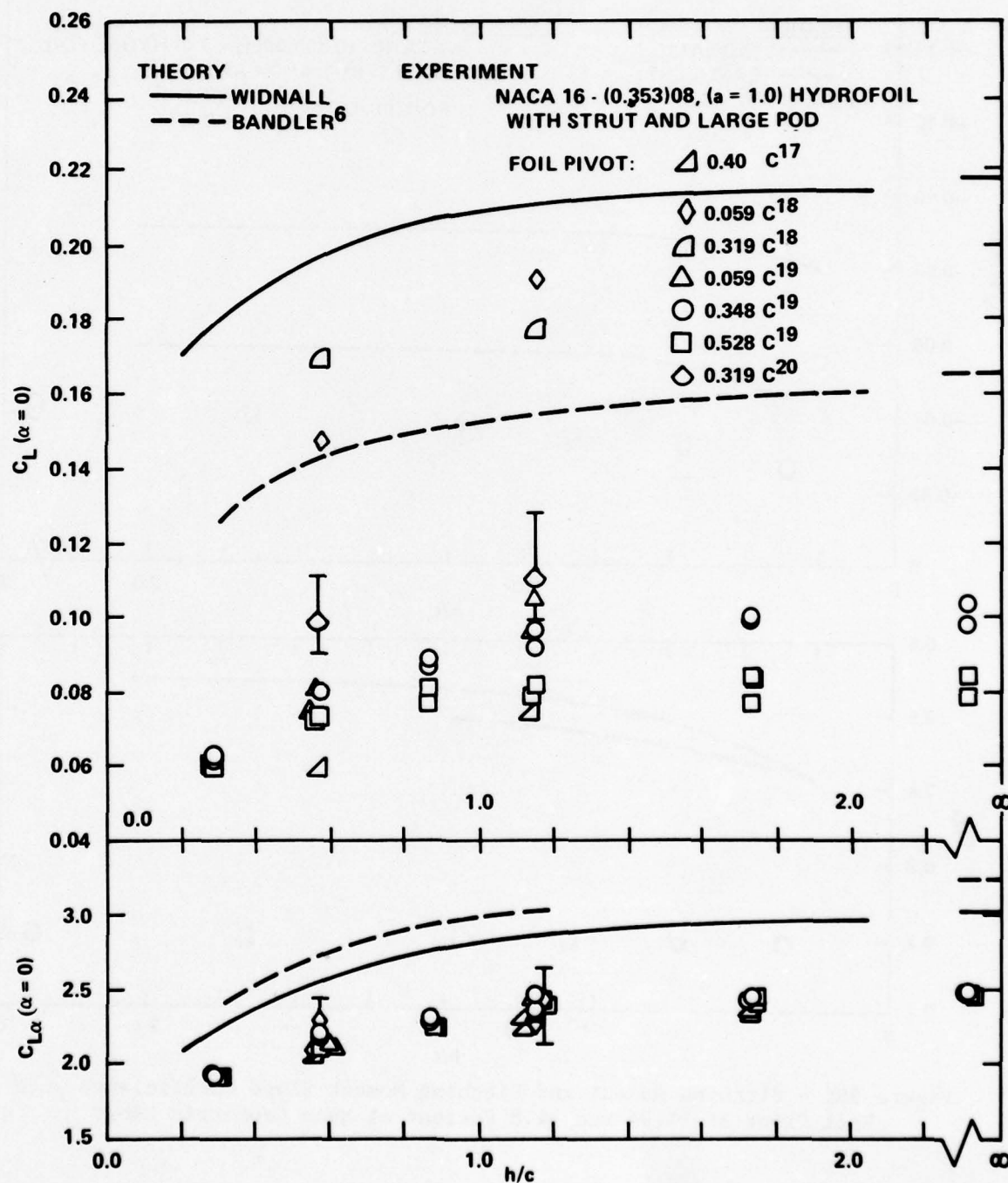


Figure 38a - Lift and Lift Slope Coefficients

Figure 38 (Continued)

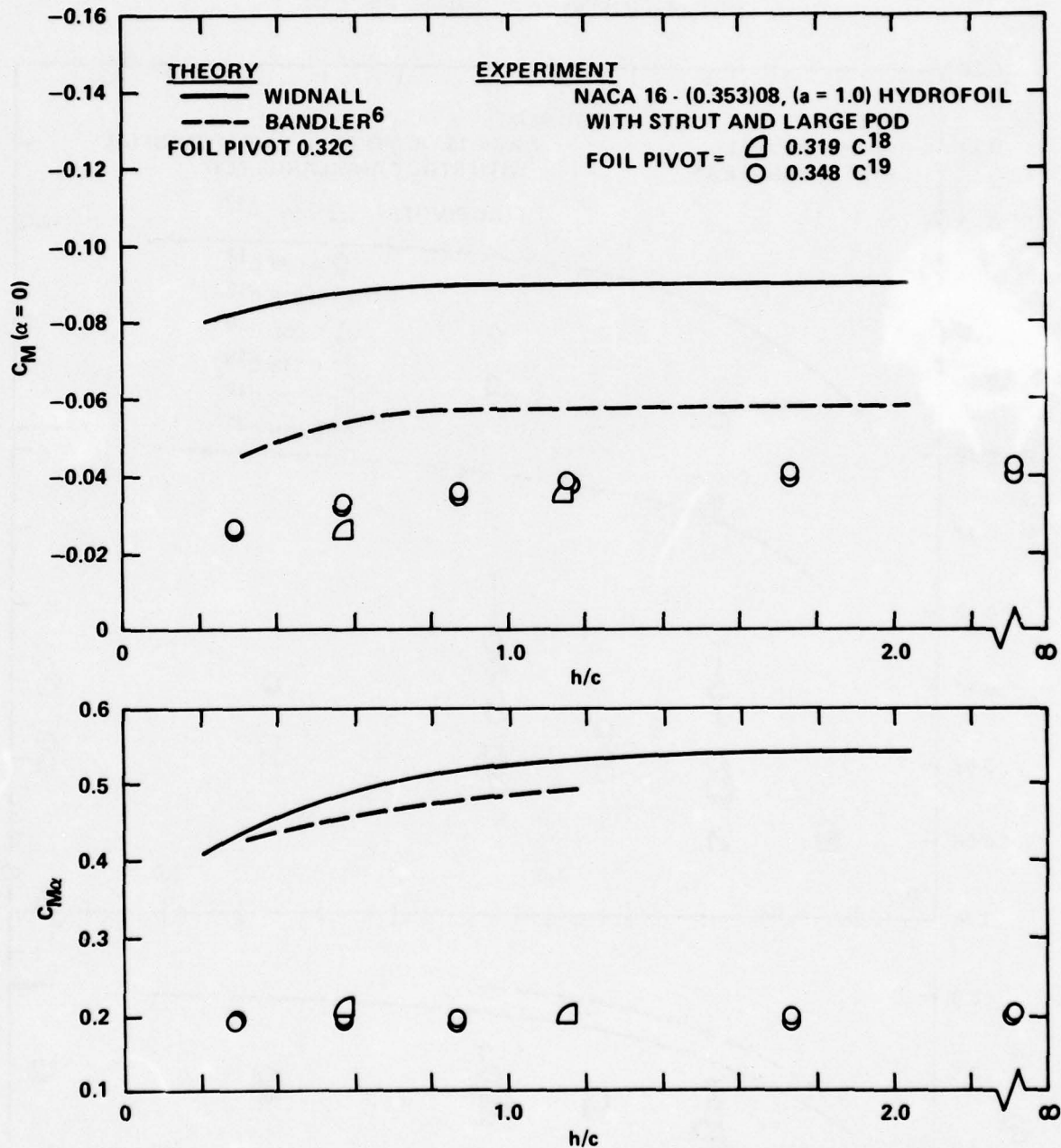


Figure 38b - Pitching Moment and Pitching Moment Slope Coefficients with Foil Pivot at 31.94 and 34.8 Percent of Mean Geometric Chord

Figure 38 (Continued)

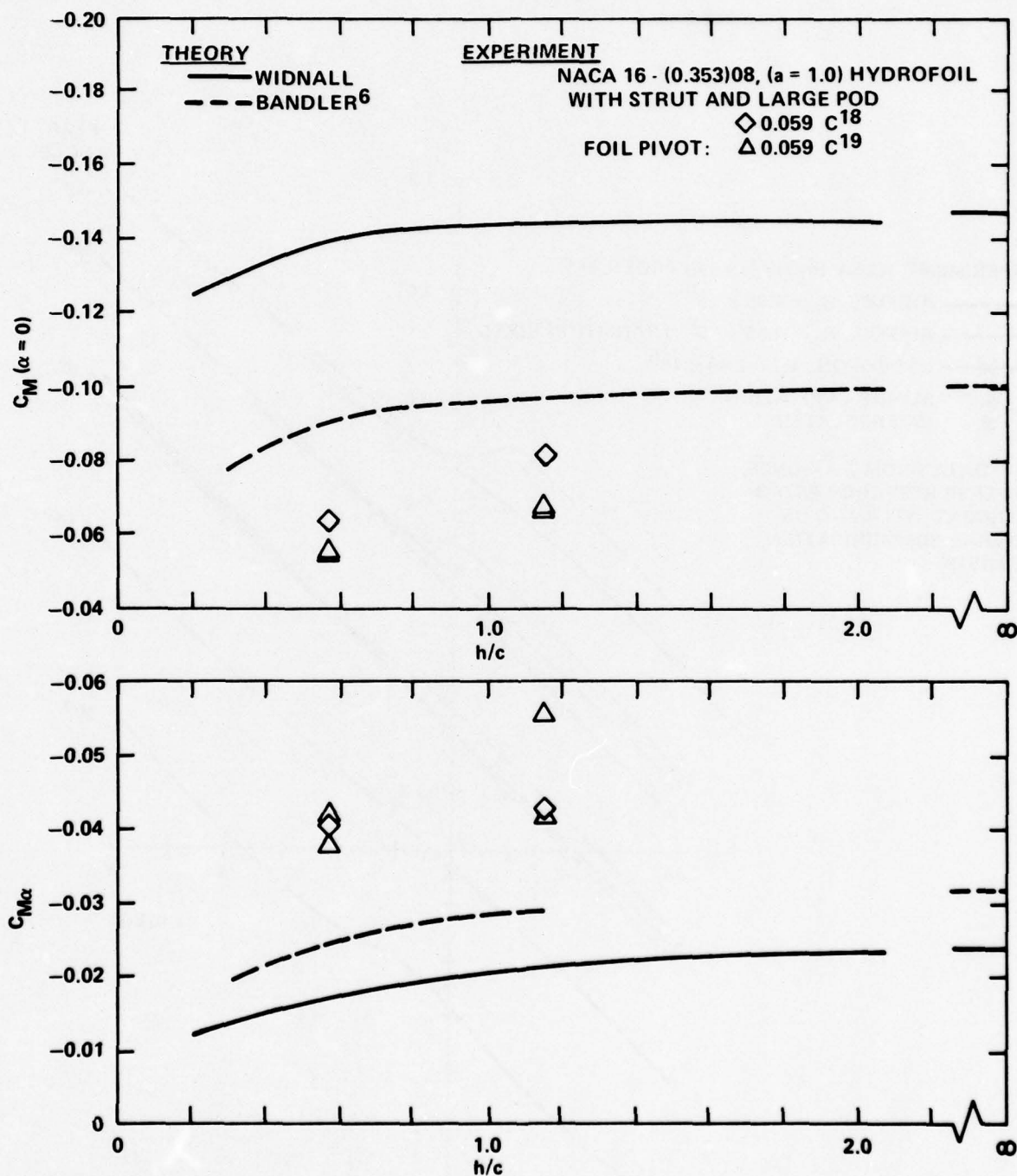


Figure 38c - Pitching Moment and Pitching Moment Slope Coefficients with Foil Pivot at 5.9 Percent of Mean Geometric Chord

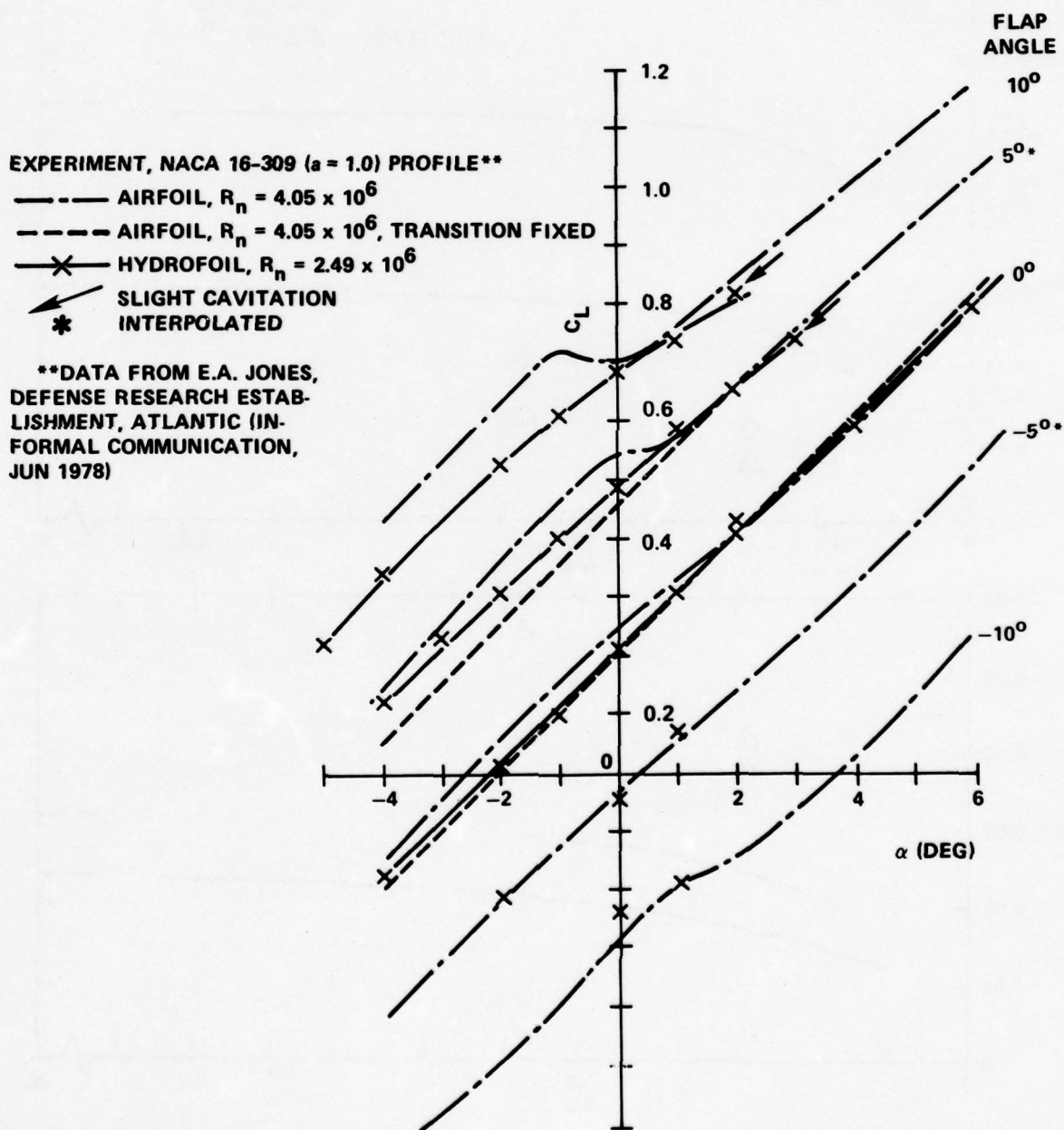
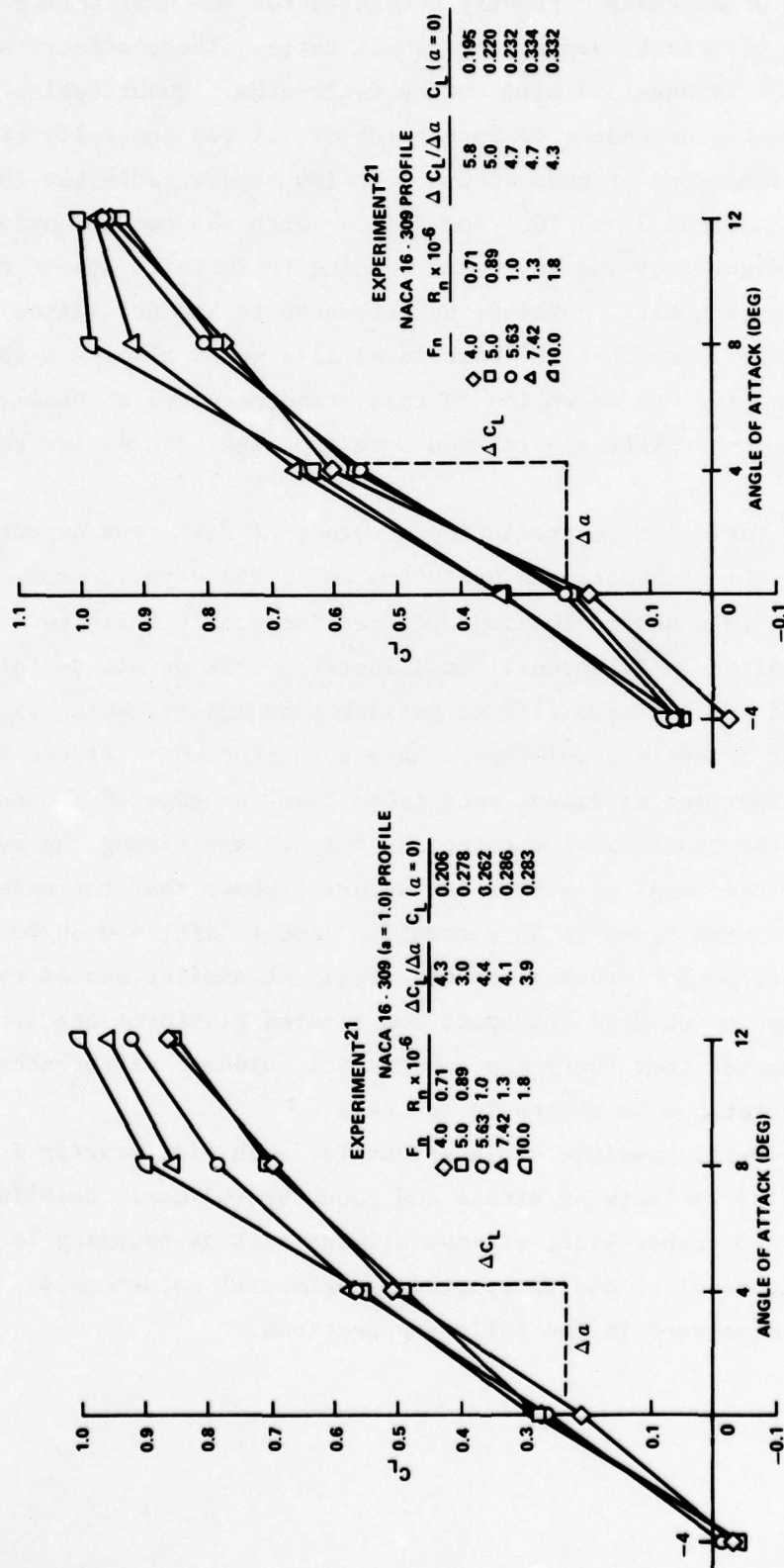


Figure 39 - Comparison of Total Lift Coefficients on a Hydrofoil and an Airfoil in Two-Dimensional Flow



The loading predictions correctly accounted for the qualitative effects of camber, angle of attack, depth, and aspect ratio. These effects are well known to most readers and will not be dwelt upon. Quantitatively, the accuracy was strongly dependent on aspect ratio: it was generally true that the predictions were of good accuracy at low aspect ratio but too high at aspect ratios between 3 and 10. Comparisons with the two-dimensional loading data in Figures 39 and 40, corresponding to infinite aspect ratio, could not be made directly. However, by reference to the prediction at $AR = 10$, it will be shown that the calculated lift would also be high at infinite aspect ratio. An exception to this trend occurred at shallow submergences, where camber lift predictions were too high even at low values of aspect ratio.

Besides the variation in prediction accuracy at different aspect ratios, it is striking to note the variation among the data themselves. Large differences in measured loading occurred for models which were either similar or only slightly different. To illustrate this point, deviations between predicted and measured lift at maximum submergence, which usually produced the most accurate predictions, have been plotted in Figure 41. When possible, experimental values were taken from the edge of the error band closest to the theoretical prediction, further minimizing the resulting deviation. This "map" of prediction accuracy shows that the experimental values differed by up to 50 percent in camber lift, and up to 29 percent in lift slope for rectangular hydrofoils at similar aspect ratios, and by even larger amounts if the swept and tapered planforms are included. These results suggest that there are substantial "hidden" differences in the model configurations or errors in the data.

There are several possible explanations for such wide scatter in the data. These include effects of struts and pods, hydrodynamic peculiarity of the NACA $a = 1.0$ camber line, viscous effects such as boundary layer transition and separation, and unreported experimental uncertainty. These effects will be discussed in the following sections.

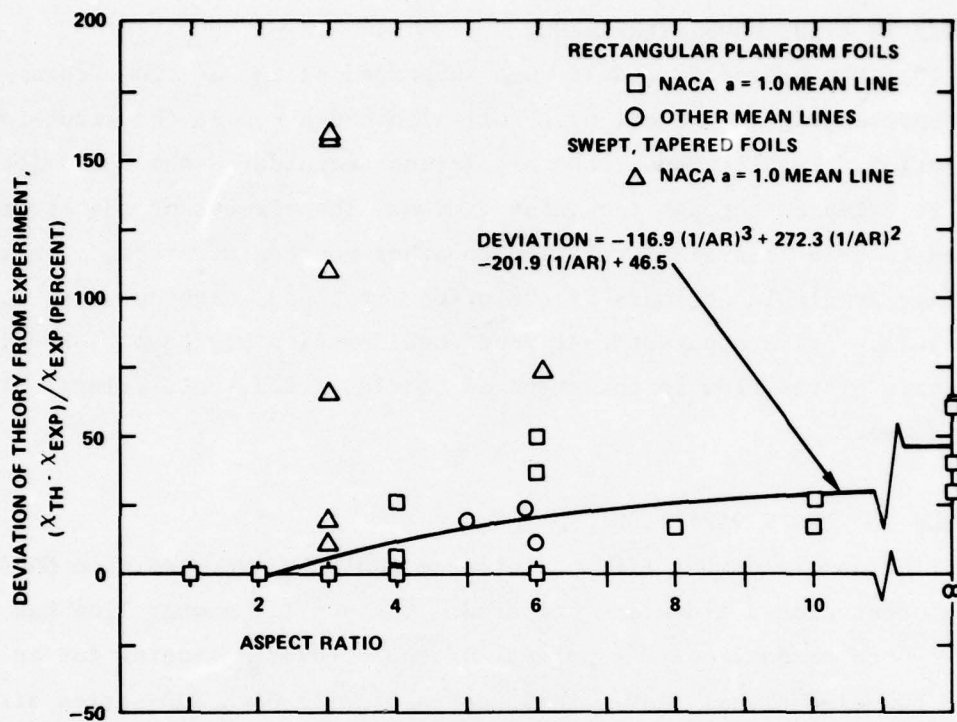


Figure 41a - $C_L (\alpha = 0)$

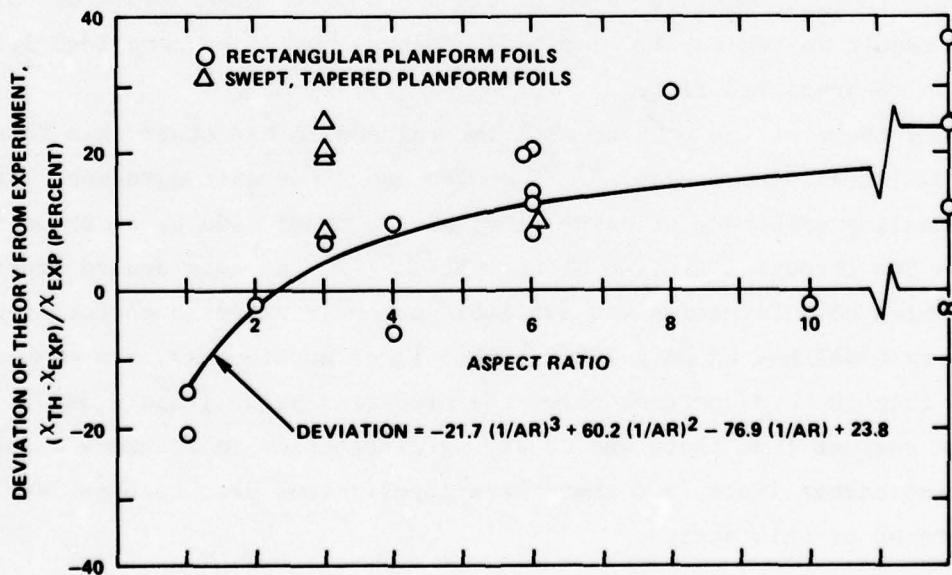


Figure 41b - $C_{L\alpha}$

Figure 41 - Prediction Accuracy of the Widnall Program as a Function of Aspect Ratio for Steady Lift at Deep Submergence

ERROR DUE TO STRUT-POD INTERFERENCE

All of the hydrofoil models were supported by one or two struts. The model representing the AGEH-1 main foil also had a pod at the strut-foil intersection. In all cases, the calculations considered the foil alone as though it extended through the strut or pod. The effects of the strut are believed to have been small relative to other sources of error. There is no readily available estimate of the effect of a pod which does not rotate with a foil. It is apparent that more consideration may have to be given to an analysis of the flow in this type of configuration, particularly at zero incidence.

ERROR DUE TO CAMBER VARIATION

Variations in camber lift performance would be expected when NACA $a = 1.0$ and other camber lines are compared. The $a = 1.0$ camber line has been found^{22,23} to produce only 74 percent of the predicted loading for an airfoil in two-dimensional flow. This contrasts with NACA 230-series airfoil sections, which produced 108 percent of the predicted loading, and NACA four-digit airfoil sections, which produced 93 percent of the predicted loading. Thus, comparisons between the $a = 1.0$ and other types of camber should result in the $a = 1.0$ sections having about 25 percent less lift, relative to predicted lift.

Only three of the present experimental models had other than NACA $a = 1.0$ mean lines. Those models¹¹⁻¹³ showed about the same agreement with the Widnall predictions of camber lift as the other models, as shown in Figures 34e through 34g. Two of the models^{11,12} had nonstandard profiles about which no information was available on their expected performance. The third model had an NACA 23012 camber line; nonetheless, its camber lift ranged from 10 to 37 percent below the predicted value (Figure 34g). These results suggest that there was no strong distinction in accuracy among different camber lines, but there were insufficient data to establish a clear trend of this sort.

ERROR DUE TO VISCOUS EFFECTS

The accuracy of the loading predictions was not systematically affected by viscous behavior of the fluid medium (water or air). Experimental values of Reynolds number R_n ranged from 2.7×10^5 to 4.4×10^6 . These values encompassed the region in which boundary layer transition would be expected. No correlation was found between prediction accuracy and R_n .

A recent investigation by Jones* has uncovered one type of viscous effect which can influence model loading measurements. Wind tunnel measurements, shown in Figure 39, displayed a nonlinearity in lift at low angles of attack. Flow visualization observations showed that the shift was caused by movement of transition from midchord to near the leading edge on the suction side of the airfoil, as the angle of attack increased. The shift was eliminated when turbulence-stimulating strips were attached near the leading edge. Full-scale systems operating at much higher R_n would correspond to the forward transition location.

Jones' observations are important because they define a mechanism by which the camber lift can differ by as much as 22 percent between apparently similar foil models. Small imperfections in models, randomly distributed, would trigger transition at the forward location in some instances and not in others. It does not appear that the lift slope would be affected significantly, because the nonlinearity was confined to a small range of angle of attack.

ERROR DUE TO UNREPORTED EXPERIMENTAL UNCERTAINTY

Most of the data scatter appears to be caused by relatively large experimental uncertainty in the data. Two model parameters are especially suspect: angle of attack and profile geometry. Angle of attack is not easy to determine, and, in most cases, the lift due to an angle of attack of one or two degrees is equal to the entire lift due to camber. Lift slope values also would be affected if changes in angle could not be measured much more accurately than the angle itself.

*Informal communication (Jun 1978) with E.A. Jones of the Canadian Defence Research Establishment Atlantic.

Experimental uncertainty in angle of attack was rarely mentioned in the reported data. In one case, a minimum uncertainty of ± 0.5 deg could be inferred from the Feldman data.⁸ This uncertainty led to relatively wide error bands which could explain the decrease in camber lift as aspect ratio increased from 6 to 8; see Figures 34g and 34h. The tendency for camber lift data to have greater scatter than lift slope data also suggests angle of attack uncertainty, because slope would be unaffected by systematic errors in angle. These observations indicate the need for improvement in the quality of angle of attack measurements. It would also be helpful for values of experimental uncertainty to be reported in all experiments.

Errors in model profile, originating in manufacturing defects or accumulations of dirt during testing, would affect camber lift rather than lift slope. Either the mean line itself, or the transition behavior, could be affected.

Jones* described a tendency for manufacturing errors to remain constant in absolute size, and thus to become more important as model size decreases. The smaller hydrofoil models, which had chords as small as 0.10 m (3.9 in.), would seem to have been susceptible to profile errors. Offset discrepancies of 10 percent were reported by Coder,¹⁹ although these were not definitely ascribed to manufacturing error, on a foil with $c' = 0.220$ m (8.65 in.). Again, it is not common practice to report profile accuracy of models, and such information could be significant.

STATISTICAL ANALYSIS OF DATA

Despite the amount of data scatter, the assembled body of data has value as a collection of multisample²⁴ data. Such data, taken by independent investigators, are not likely to have been affected by systematic errors. Given enough points, the data will form a normal distribution for which the mean is the most probable value.

Unfortunately, there are not enough values to perform such an analysis at any one aspect ratio with the present data. Only two foil configurations have had several independent measurements made of loading characteristics. The AR = 6 rectangular hydrofoil has had four measurements

*E. A. Jones, informal communication.

made of lift slope; the measurements for the $AR = 5.84$ hydrofoil could be considered a fifth value. These measurements are too few in number to form a normal distribution. It may be useful, however, to know that the average of the five values for $C_{L\alpha}$ is 3.6 at $h/c = 2.0$. The predicted value is 4.15, or 15 percent high. Closer agreement is obtained for the three values corresponding to deeper submergence.

A second example is the AGEH-1 model, for which four measurements of lift and moment have been made.^{14,16-18} Camber lift and lift slope predictions at $h/c = 1.156$ were 130 and 23 percent, respectively, above the average of the data other than the camber lift data of Reference 18. The preponderance of the data, independent except that the same model was used (except for the addition of a sealed flap to the foil in Reference 19), strongly implies that the higher camber lift value of Reference 18 was erroneous. These results, incidentally, reemphasize the less accurate character of the camber lift prediction.

A similar analysis can be made of the two-dimensional data, for which four independent values of lift and lift slope are available:

| 2-D Data Source | Average $C_L (\alpha=0)$ | Average $C_{L\alpha}$ |
|--|-----------------------------|--------------------------|
| Lindsey (airfoil) ²⁵ | 0.24 | 6.0 |
| Jones (hydrofoil)* | 0.21 | 5.4 |
| Jones (airfoil)* | 0.21 | 5.4 |
| Robins (hydrofoil, $h/c = 3$) ²¹ | 0.26 | 4.9 |
| Data Average | 0.23 | 5.4 |

In this comparison, the Jones airfoil data corresponded to fixed transition. The Robins data are more questionable than the others because it was not certain that a completely two-dimensional flow condition was achieved. It can be seen from expressions presented by Abramson et al.²⁶ that results at $AR = 10$ are about 80 percent of the two-dimensional values.

*E. A. Jones, informal communication.

This correction was used to extrapolate the Widnall predictions from $AR = 10$ (see Table 1) to infinite aspect ratio. The predictions of lift and lift slope were then 46 and 25 percent high, respectively. These deviations were included in Figure 41.

To provide an estimate of the accuracy of the Widnall calculation over the complete range of aspect ratio, a third-order polynomial curve fit has been made to the deviations between theory and experiment as a function of the reciprocal of the aspect ratio. Only rectangular foils were included, using data from the maximum submergences. The resulting curve, replotted in Figure 41 in terms of aspect ratio, indicates that the deviation of the calculation ranges from 0 to +47 percent for camber lift and from -15 to +24 percent for lift slope, for aspect ratios of 1 and above. By applying a correction equal to the value of the fitted curve to the Widnall prediction at any aspect ratio, the resulting accuracy is expected to be within ± 15 percent of the value measured in a series of independent experiments. It appears that a higher degree of accuracy could be ascribed to the corrected predictions if more data were available to define the correction in a statistically more rigorous manner.

In view of the large amount of data showing the effect of varying submergence, a further correction could be determined which would extend the Widnall predictions to shallow submergences with little probable loss of accuracy. This correction was not determined in the present study.

COMPARISON WITH THE BANDLER PROGRAM

The Bandler loading calculation,⁶ included in Figures 34, 35, 37, and 38, provided what appears to be much more accurate predictions than the Widnall calculation. In particular, the Bandler program predicted substantially lower values of camber lift than the Widnall program. However, in view of the probable influence of viscous effects in lowering camber lift for $NACA a = 1.0$ mean line sections, the Bandler program (which also did not consider viscosity) is thought to have underpredicted camber lift. A further deficiency of the calculation involved numerical instability. Unpublished calculations showed that the numerical stability of the program

was limited to one or two significant figures. A severe limitation in the number of control points, and hence pressure modes (only sixteen collocation points were allowed) prevented proper exploration of this aspect. It is concluded that the Bandler calculation is not suitable for loading prediction in its present form, but should be reformulated to ensure numerical stability. This effort would be particularly desirable because the analysis permits inclusion of foil thickness and, in an unusual feature among existing theories, predicts the effects of gravity wave generation (finite Froude number) on foil loading.

UNSTEADY LOADING--THEORY AND EXPERIMENT

The unsteady loading predictions of the Widnall program were compared with data from four hydrofoil and two airfoil model configurations.^{15,18,27-32} The models are described in Appendix A. Comparisons were also made with other theoretical results, namely, the Woolston et al. lifting-surface program,³¹ a quasi-steady calculation,³² and a two-dimensional version of the Widnall calculation.¹⁸ The results are shown in Figures 42 through 49. In each case, the calculated results are shown in the form presented by the experimental investigator. Predictions for each of the models will be described in the following sections.

OSCILLATING FOILS

Results for loading produced by forced oscillation of foils are shown in Figures 42 through 46. Individual model results are discussed in the following sections.

NACA 66-209(S) Hydrofoil

The lift due to heave oscillation of an aspect ratio 5 rectangular hydrofoil²⁷ is shown in Figure 42. At the intermediate depth used in the calculation, the predicted lift was always larger than the experimental lift, with the error increasing at larger reduced frequency. The maximum error was approximately 40 percent. The phase angle was predicted well except at shallow depths where the calculated value led the experimental value by up to 20 deg.

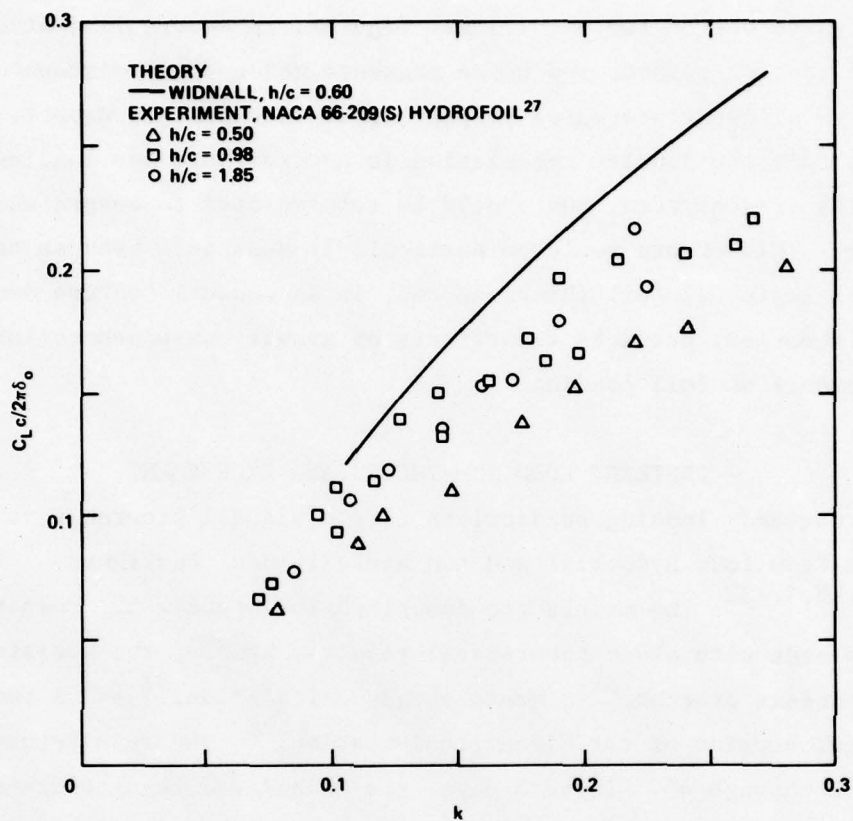


Figure 42a - Magnitude of Lift Coefficient

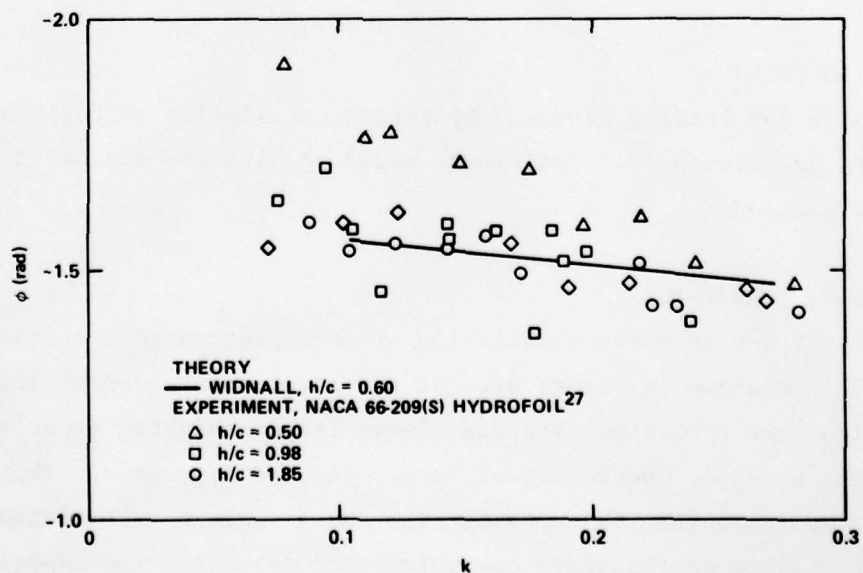


Figure 42b - Phase Angle of Lift Coefficient

Figure 42 - Total Unsteady Lift Coefficient due to Heave Oscillation
 as a Function of Reduced Frequency for the NACA 66-209(S)
 Hydrofoil ($\Lambda = 0$; $\tau = 1.0$; $AR = 5$)

Figure 43 - Spanwise Distributions of Unsteady Loading due to Bending and Torsional Oscillations for the NACA 0010 Airfoil
($\Lambda = 0$; $\tau = 1$; $AR = 5$)

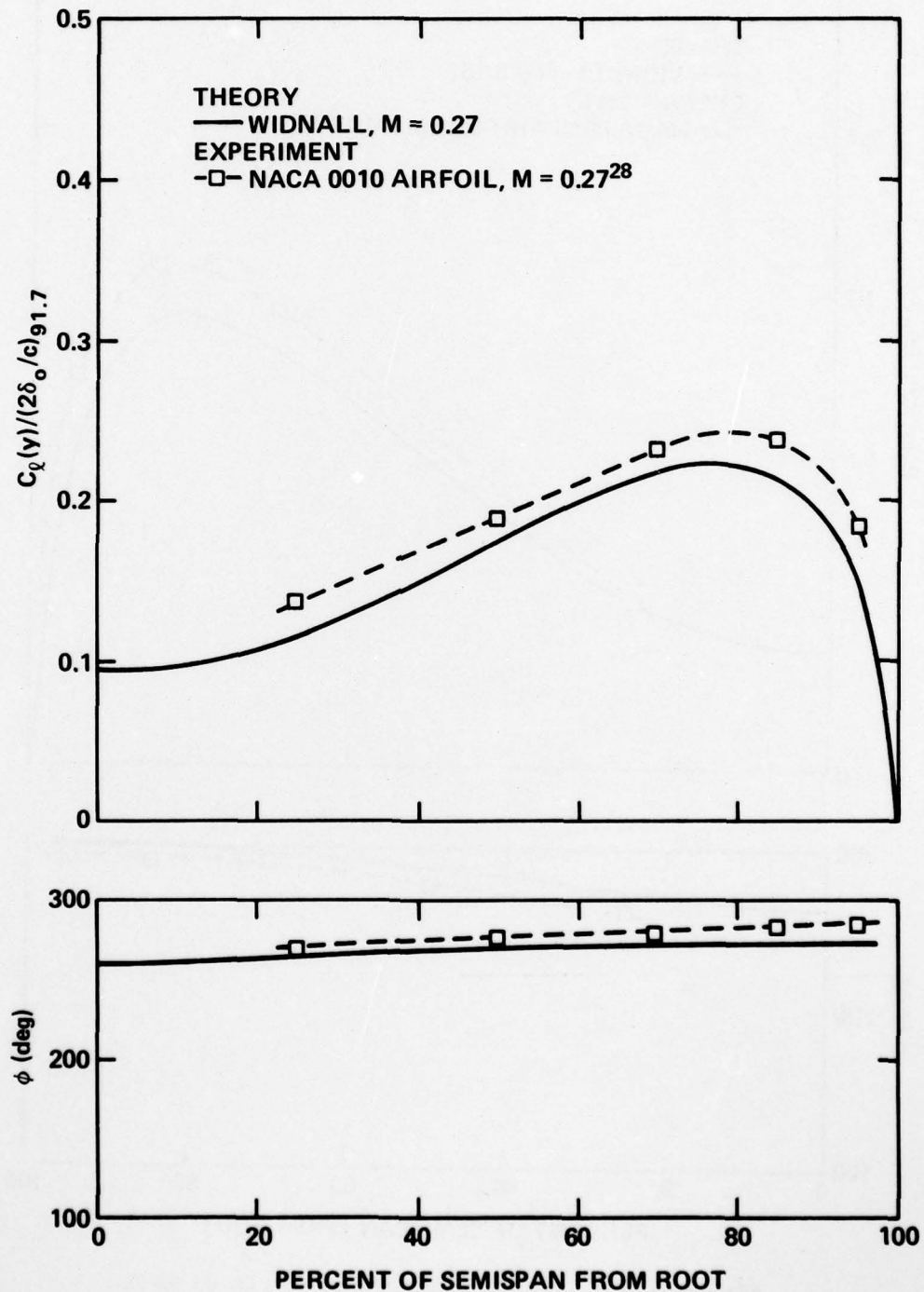


Figure 43a - Magnitude and Phase Angle of Lift Coefficient due to Bending at $k = 0.1$

Figure 43 (Continued)

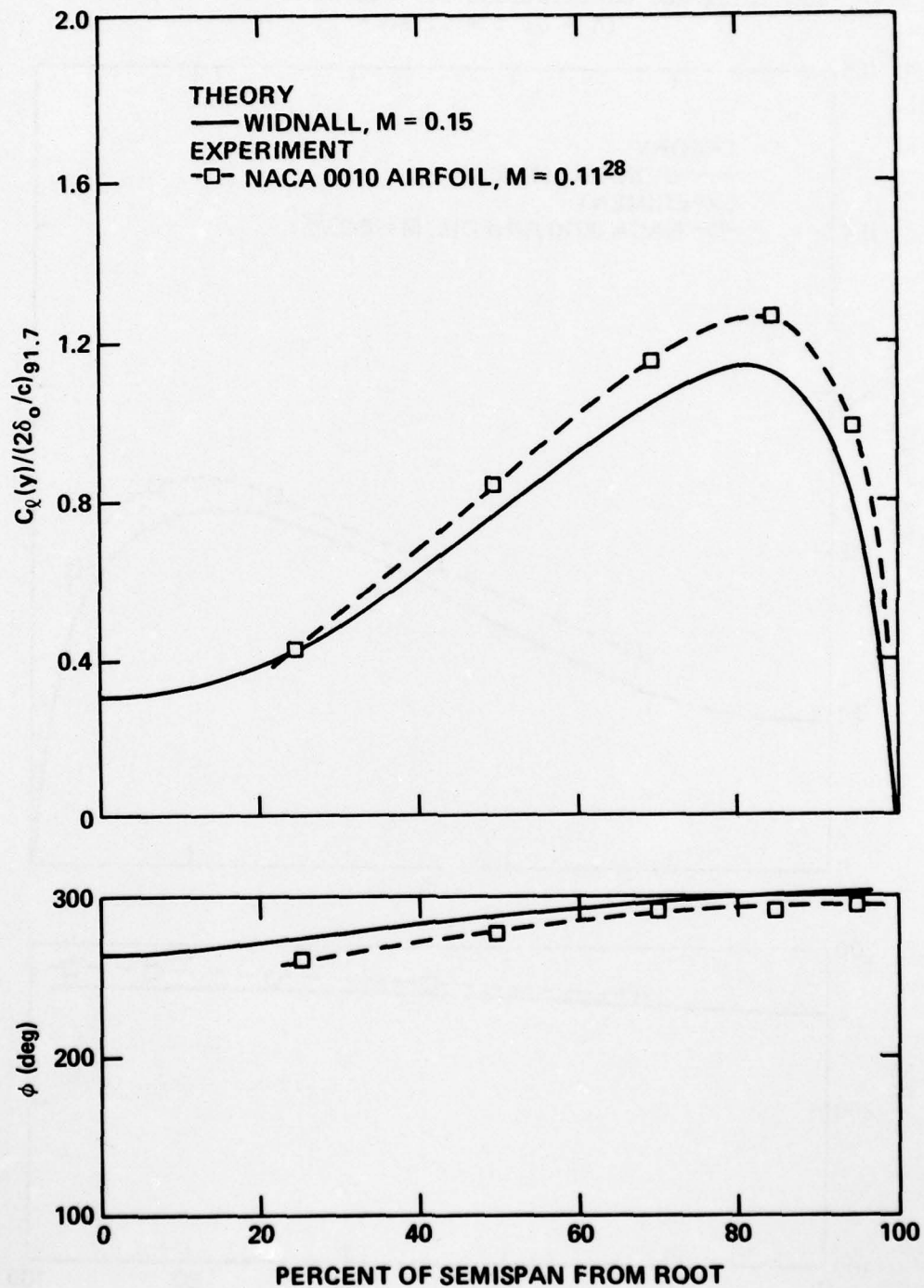


Figure 43b - Magnitude and Phase Angle of Lift Coefficient due to Bending at $k = 0.5$

Figure 43 (Continued)

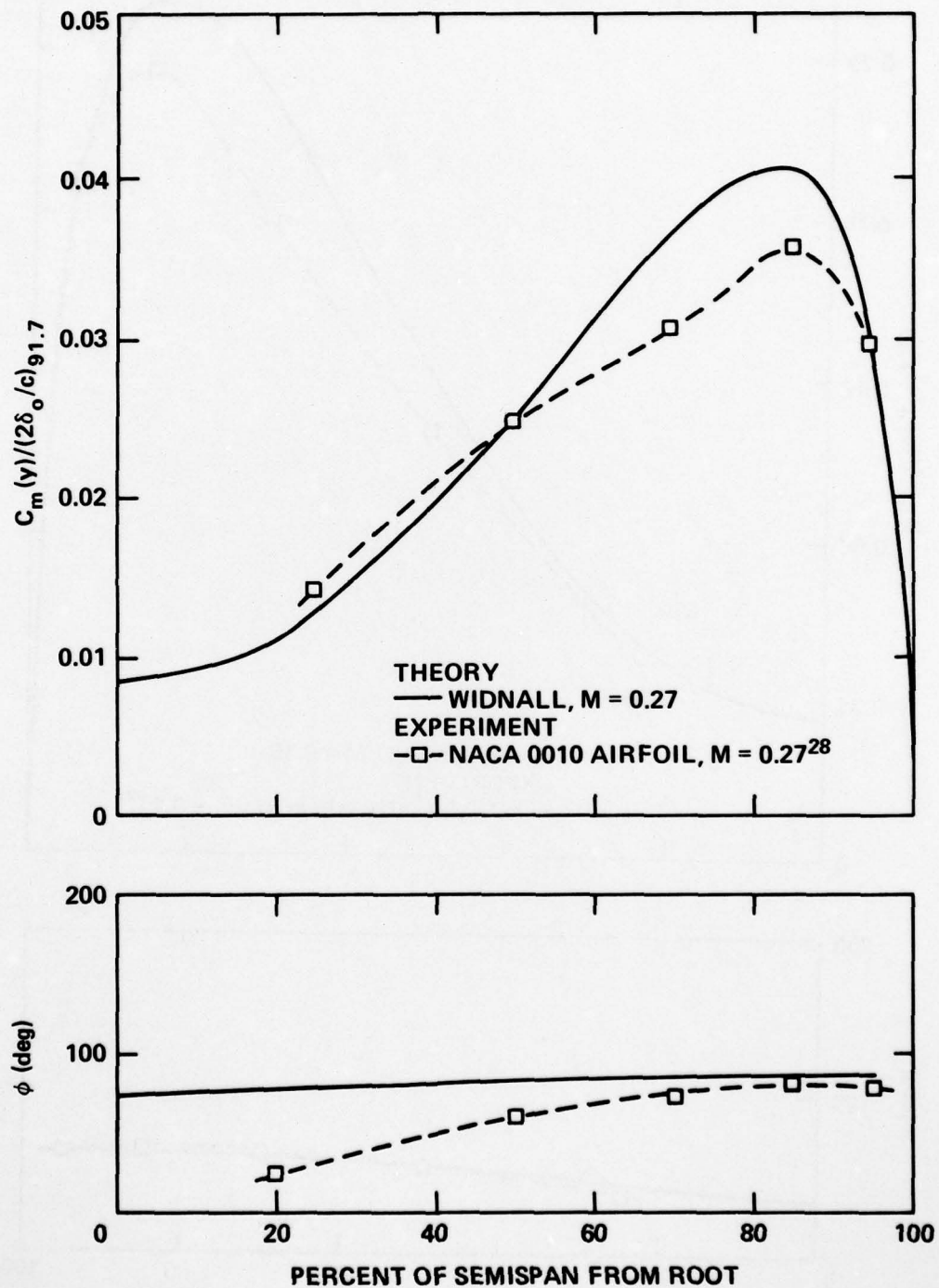


Figure 43c - Magnitude and Phase Angle of Pitching Moment Coefficient due to Bending at $k = 0.1$

Figure 43 (Continued)

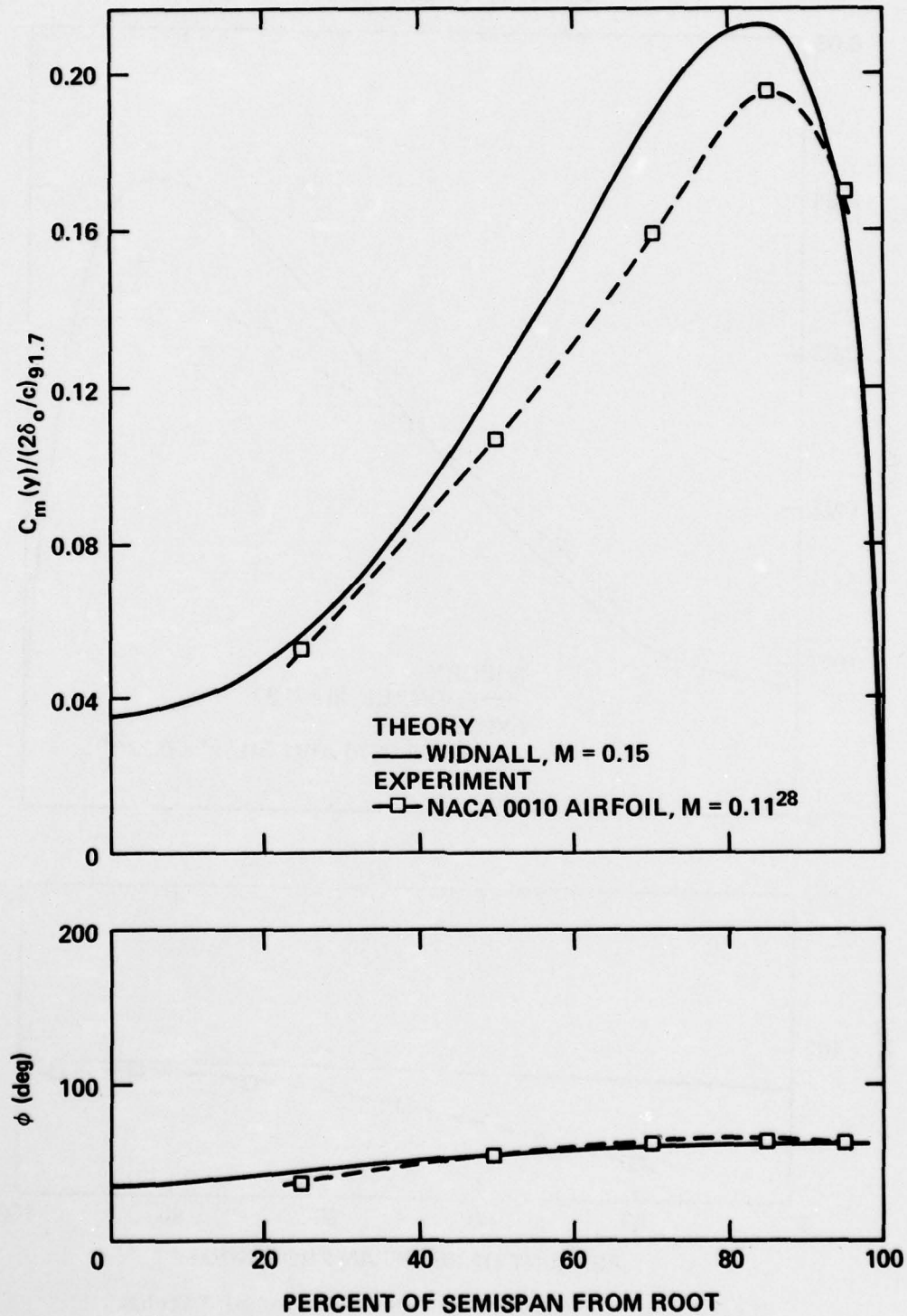


Figure 43d - Magnitude and Phase Angle of Pitching Moment Coefficient due to Bending at $k = 0.5$

Figure 43 (Continued)

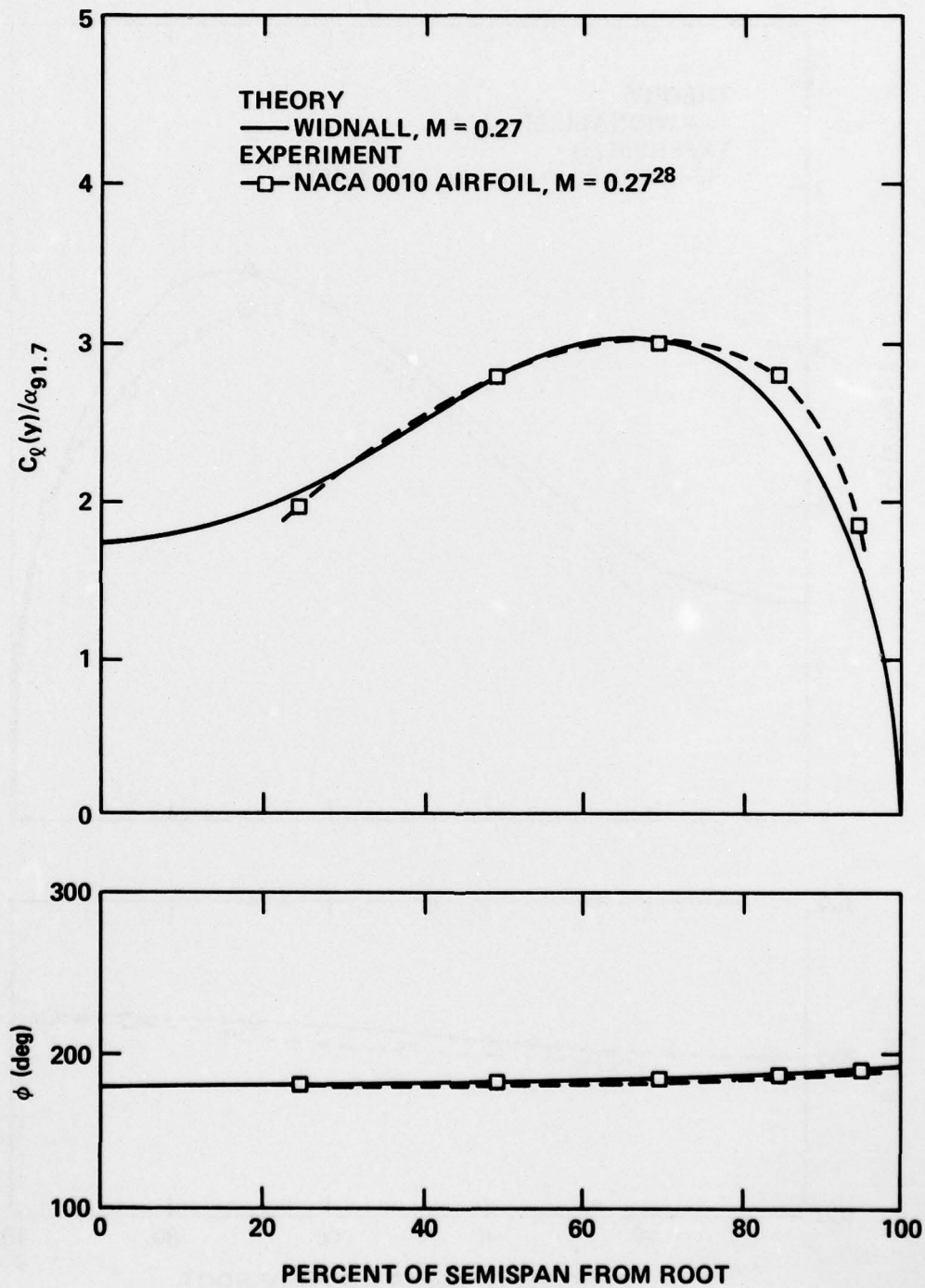


Figure 43e - Magnitude and Phase Angle of Lift Coefficient due to Torsion at $k = 0.1$

Figure 43 (Continued)

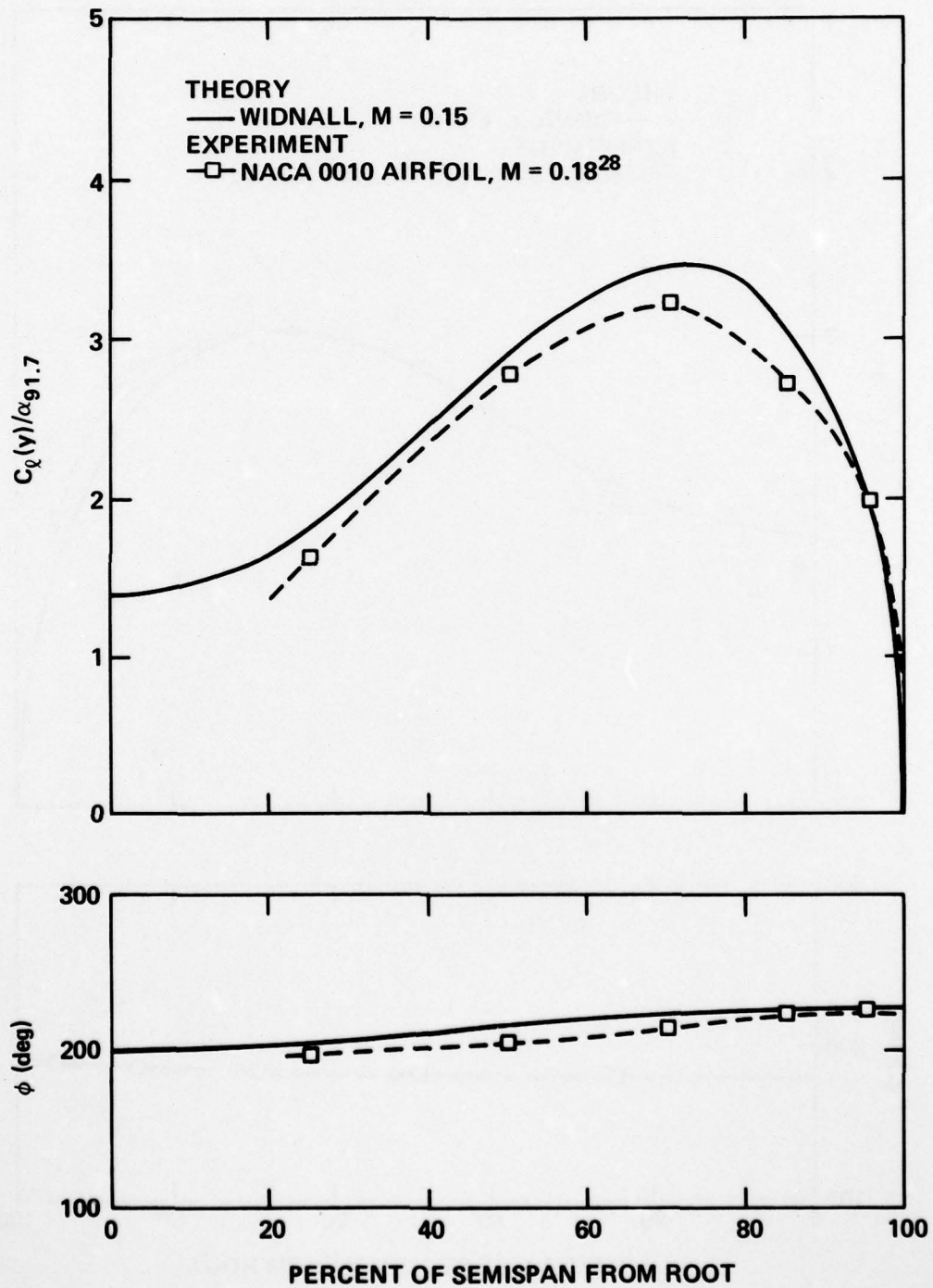


Figure 43f - Magnitude and Phase Angle of Lift Coefficient due to Torsion at $k = 0.5$

Figure 43 (Continued)

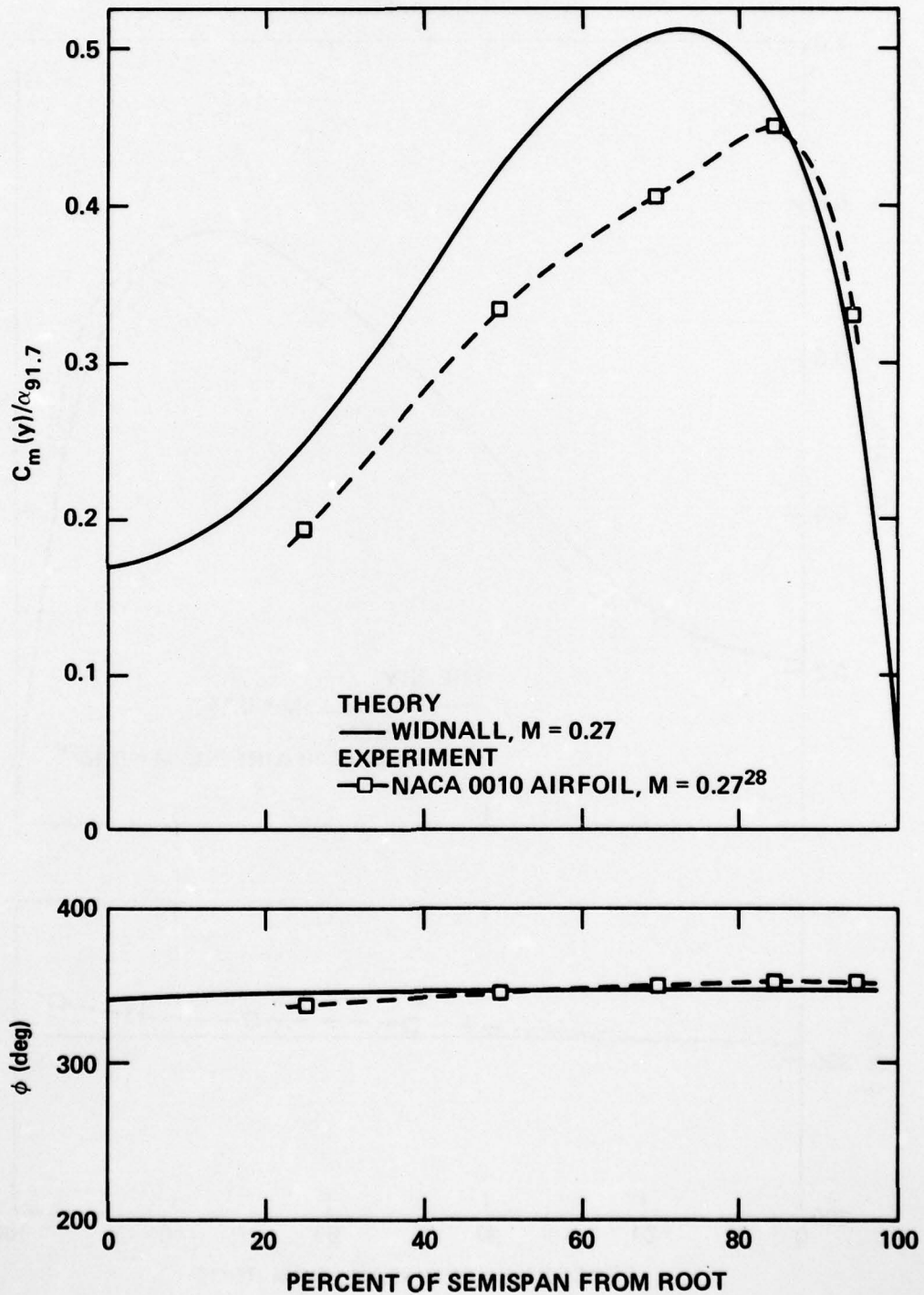


Figure 43g - Magnitude and Phase Angle of Pitching Moment Coefficient due to Torsion at $k = 0.1$

Figure 43 (Continued)

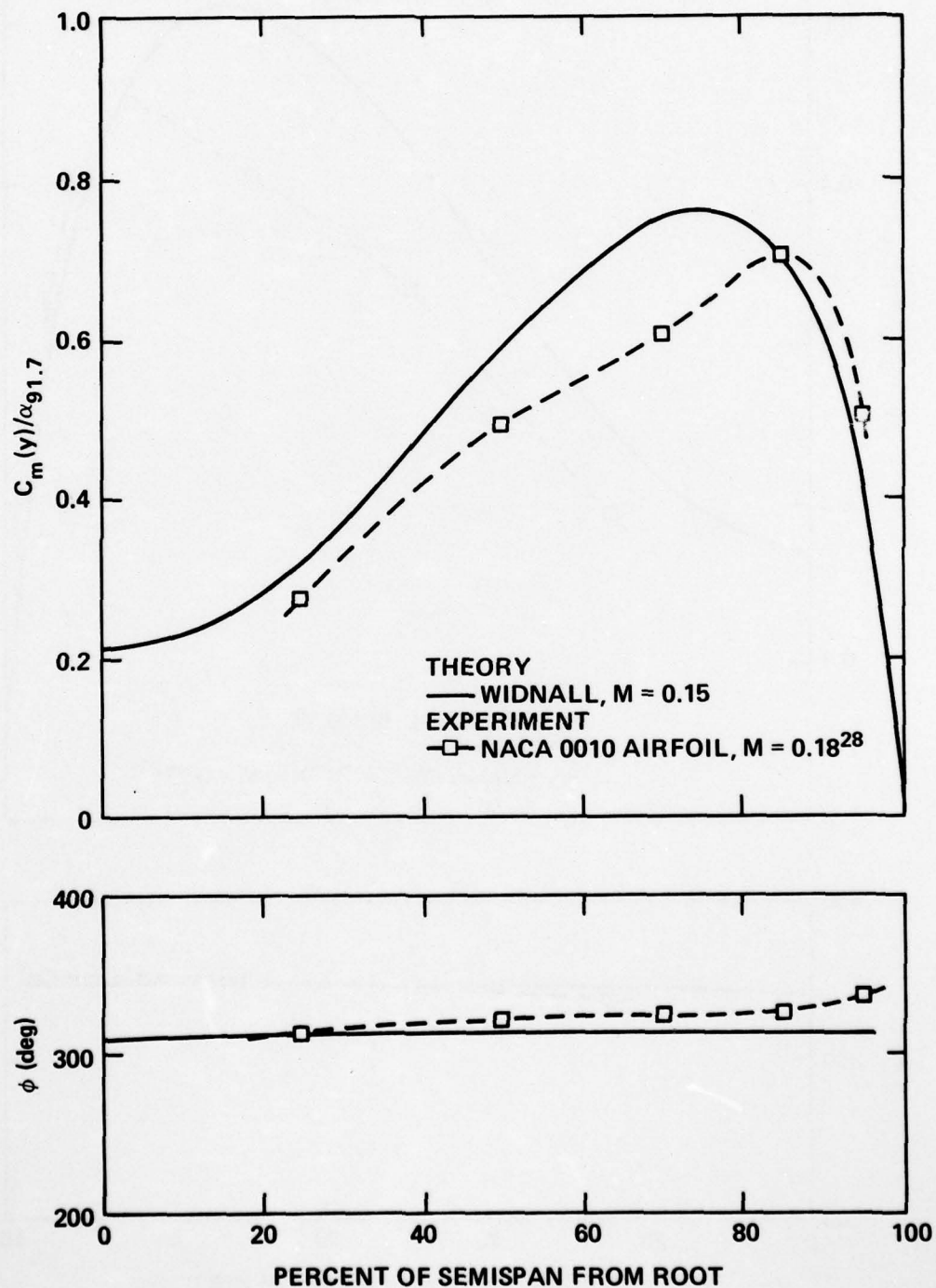


Figure 43h - Magnitude and Phase Angle of Pitching Moment Coefficient due to Torsion at $k = 0.5$

Figure 44 - Spanwise Distributions of Unsteady Loading due to Bending and Torsional Oscillations for the NACA 0010 Hydrofoil
($\Lambda = 0$; $\tau = 1$; $AR = 5$)

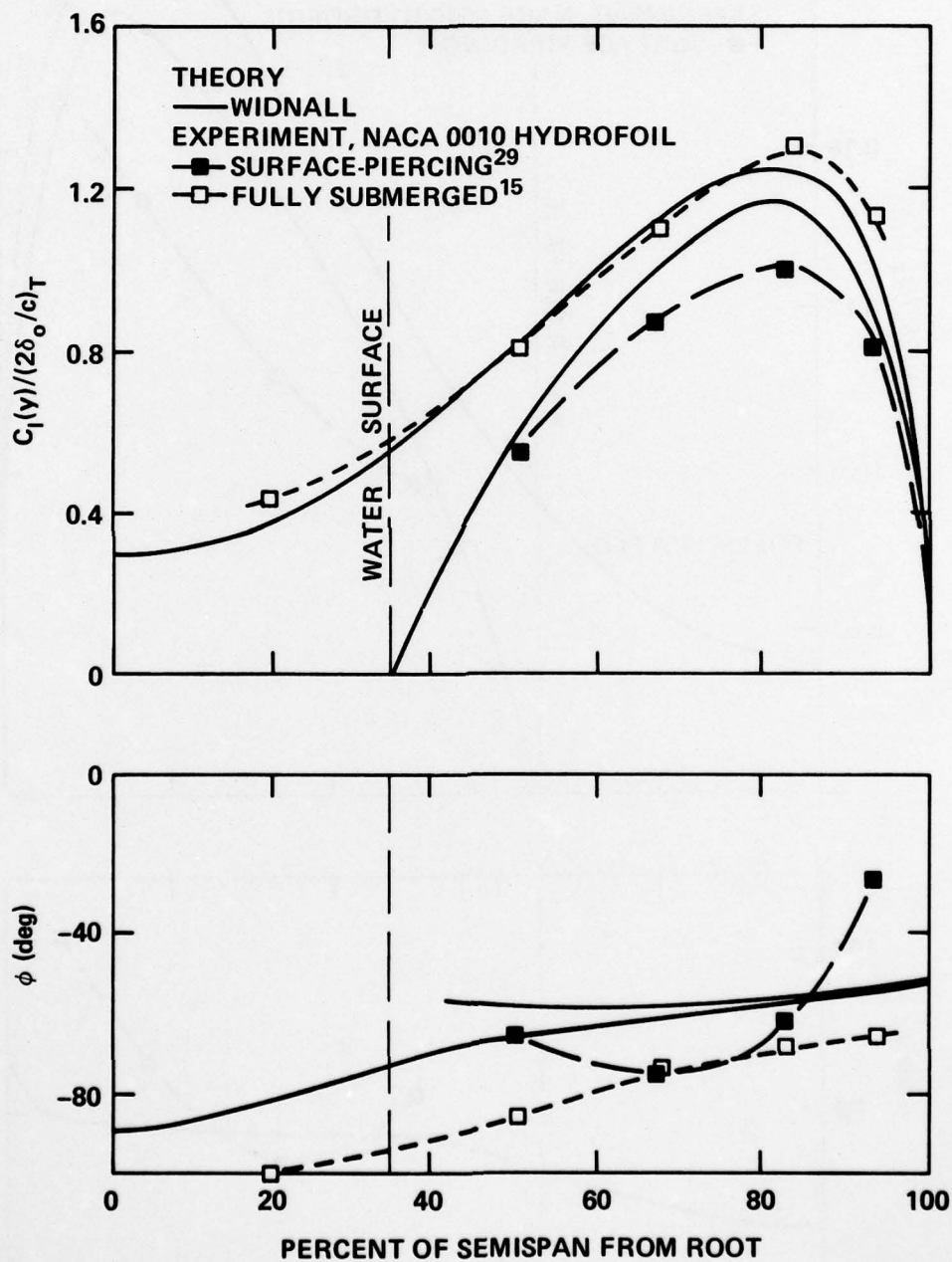


Figure 44a - Magnitude and Phase Angle of Lift Coefficient due to Bending at $k = 0.6$

Figure 44 (Continued)

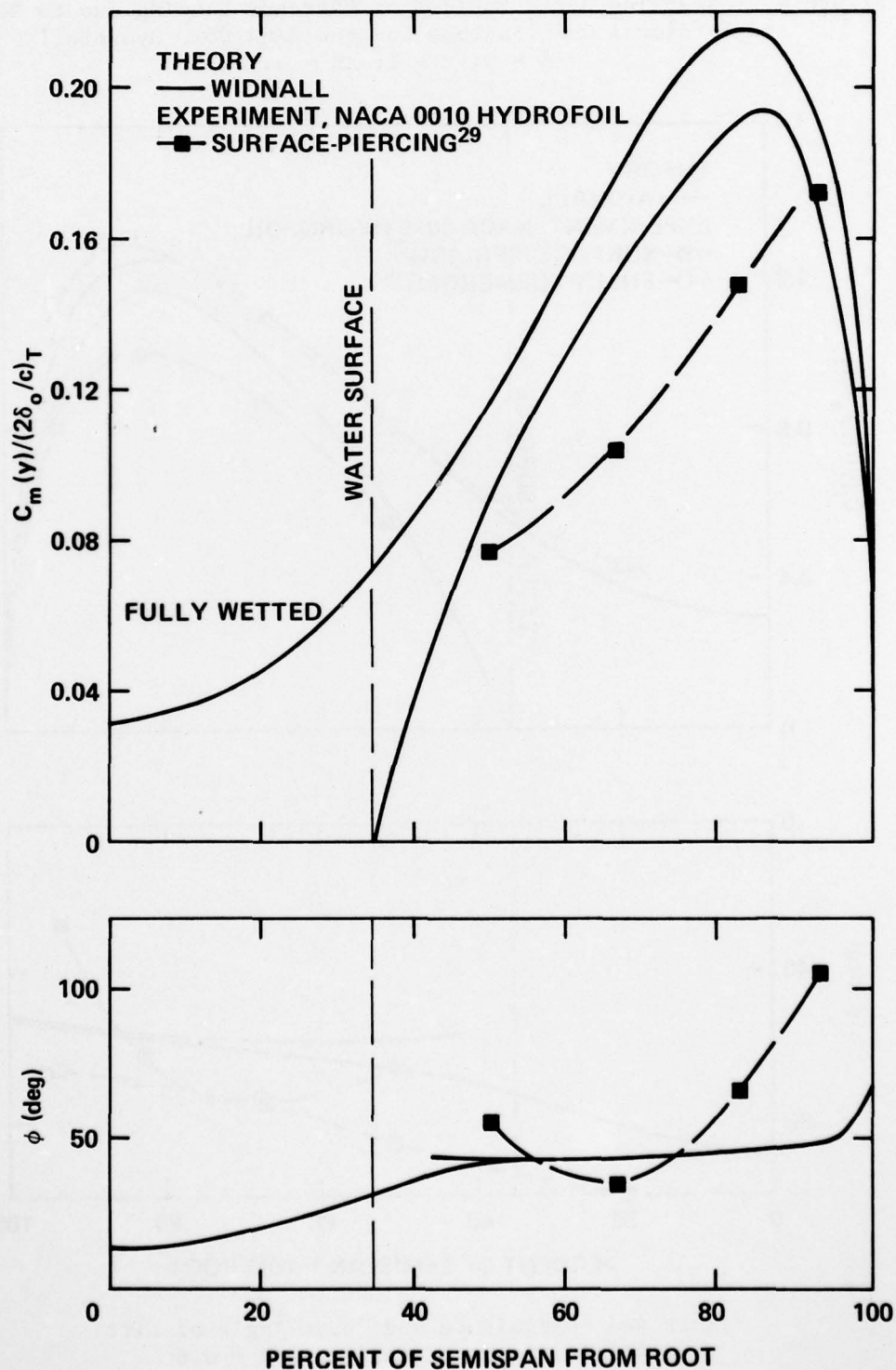


Figure 44b - Magnitude and Phase Angle of Pitching Moment Coefficient due to Bending at $k = 0.6$

Figure 44 (Continued)

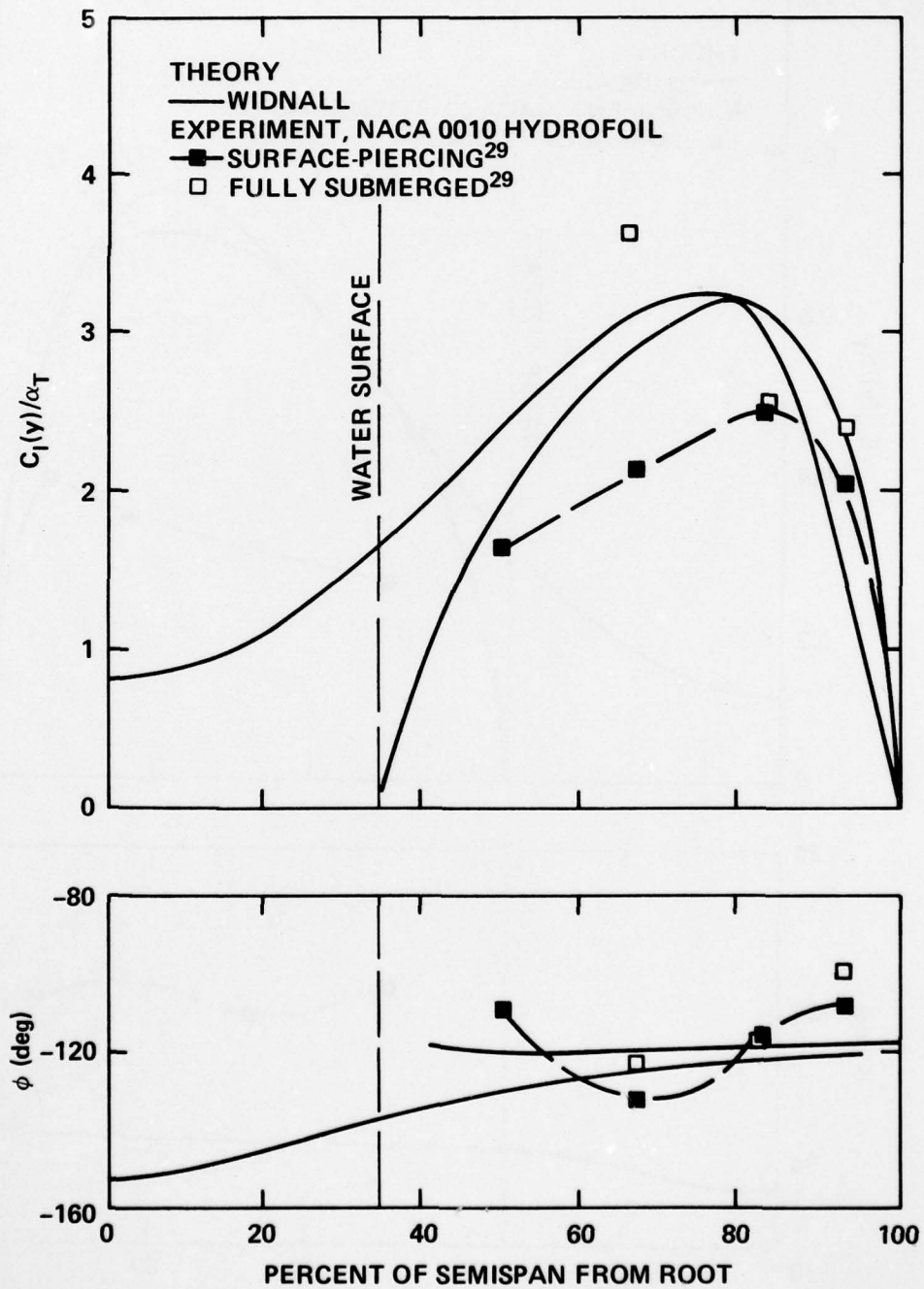


Figure 44c - Magnitude and Phase Angle of Lift Coefficient due to Torsion at $k = 0.6$

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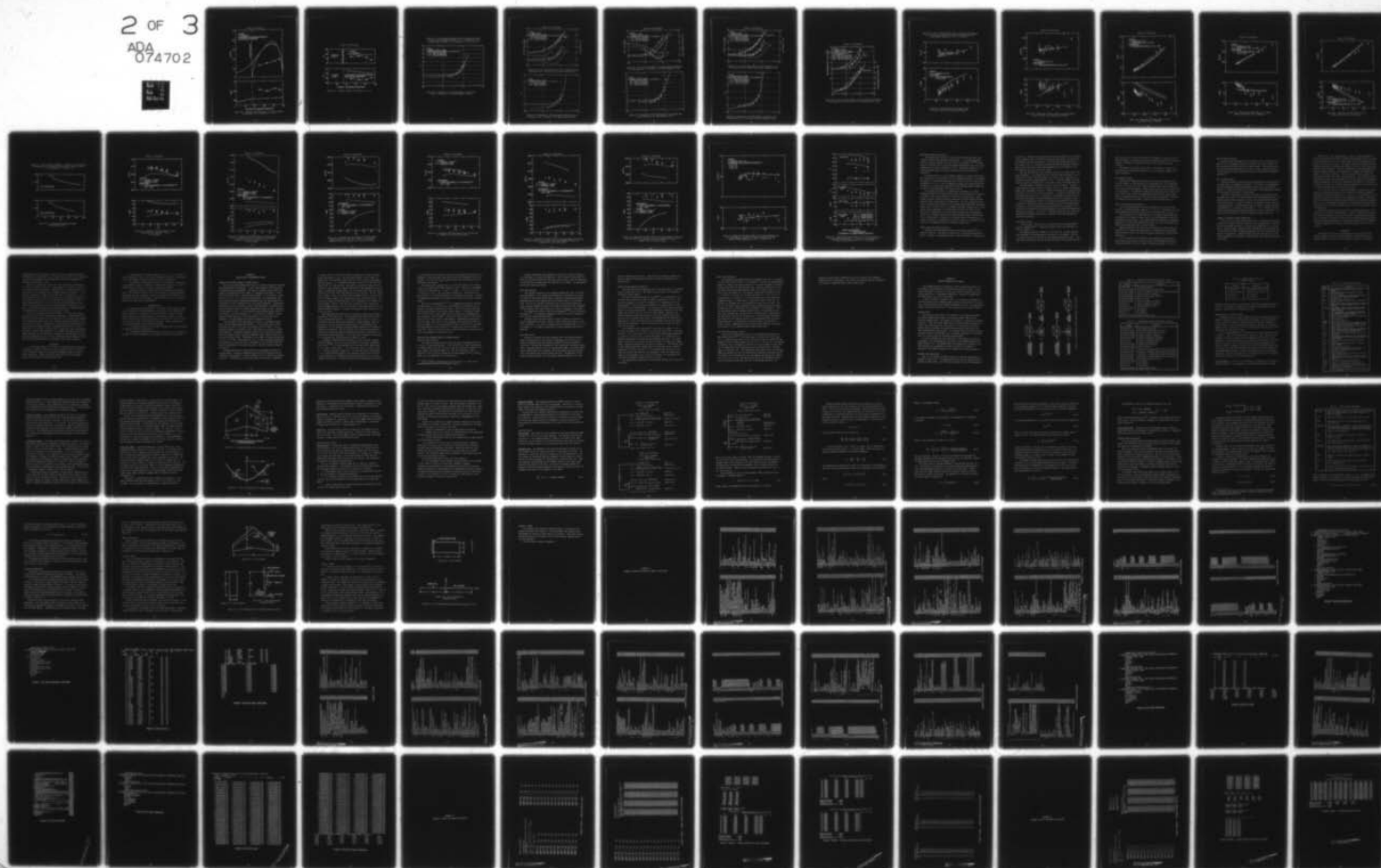
DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CE--ETC F/6 13/10
ACCURACY OF HYDROFOIL LOADING PREDICTIONS OBTAINED FROM A LIFTI--ETC(U)
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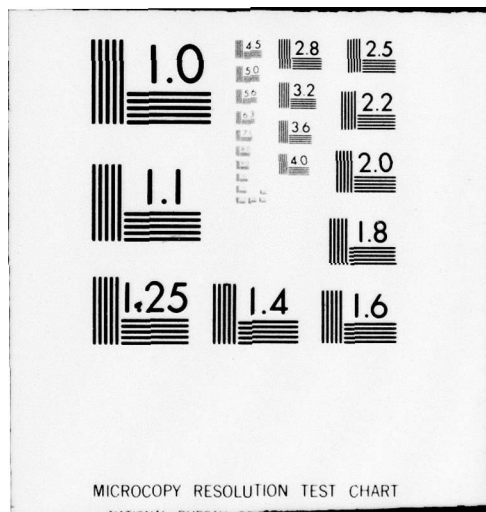


Figure 44 (Continued)

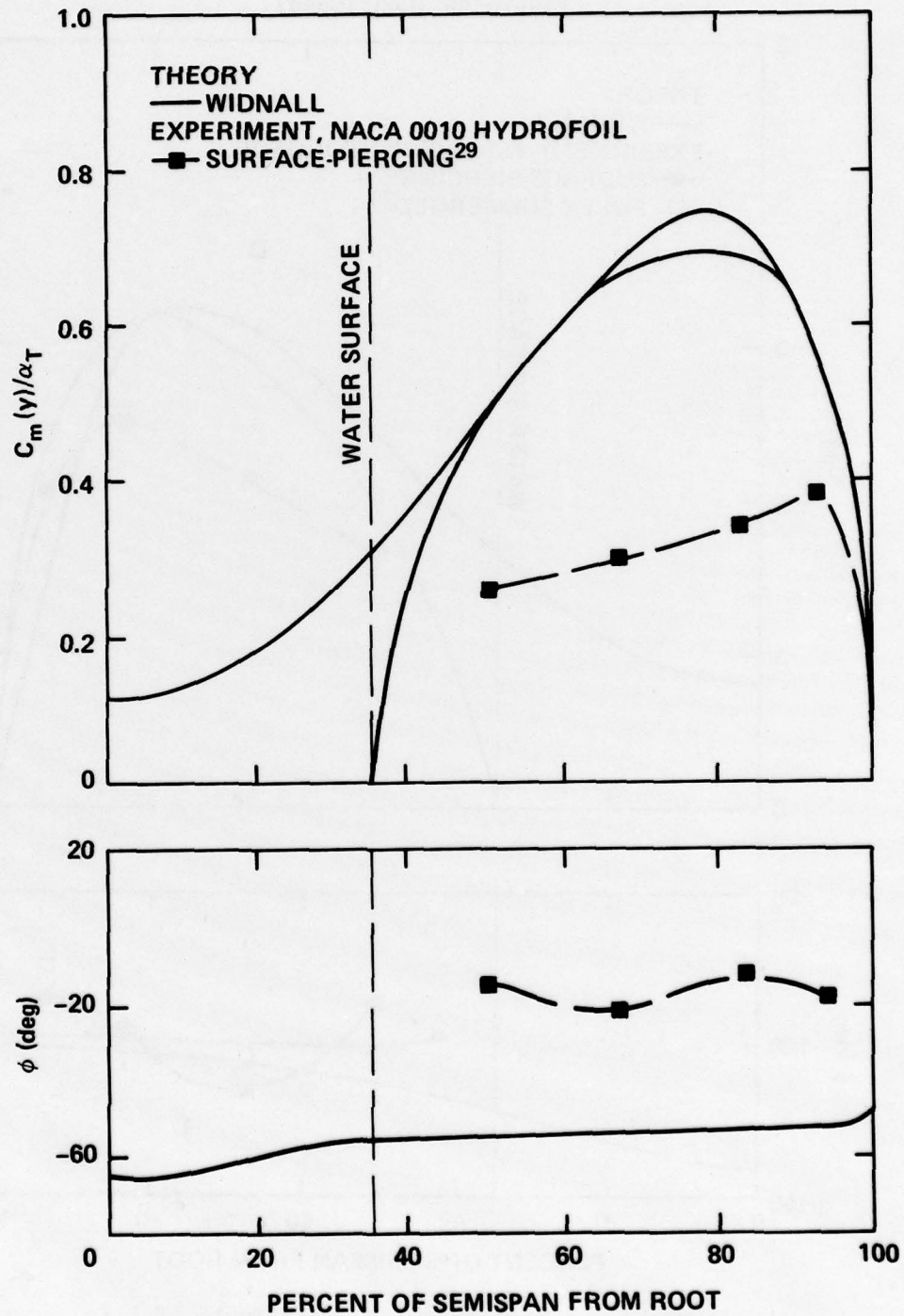


Figure 44d - Magnitude and Phase Angle of Pitching Moment Coefficient due to Torsion at $k = 0.6$

Figure 44 (Continued)

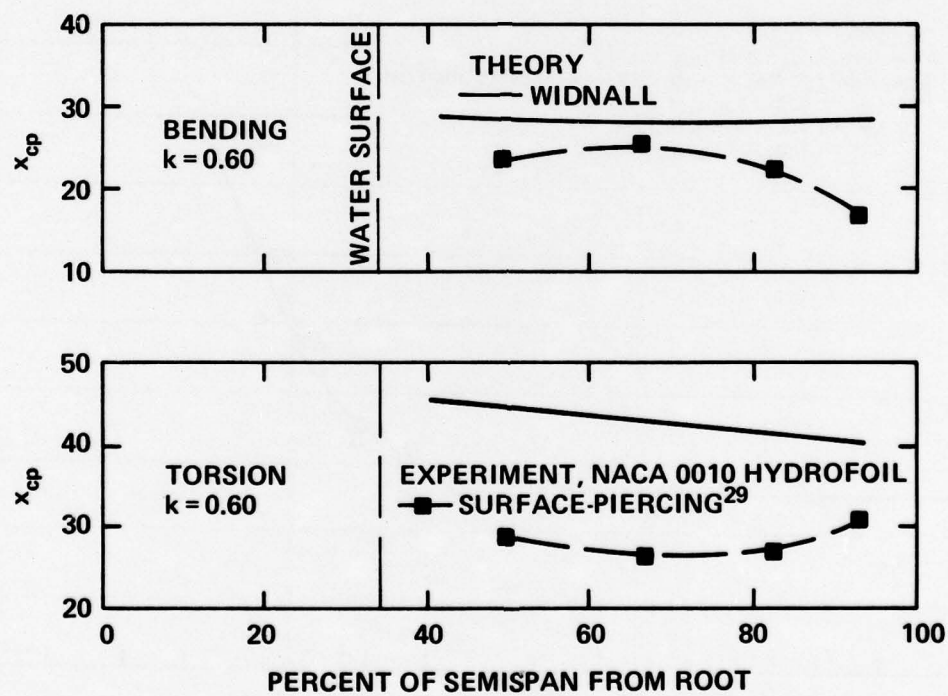


Figure 44e - Unsteady Center of Pressure at $k = 0.6$

Figure 45 - Total Unsteady Loading due to Pitching Oscillation
as a Function of Reduced Frequency for the One-Twelfth-Scale
AGEH-1 Hydrofoil Model ($\Lambda = 35$ Degrees; $\tau = 0.3$; $AR = 3$)

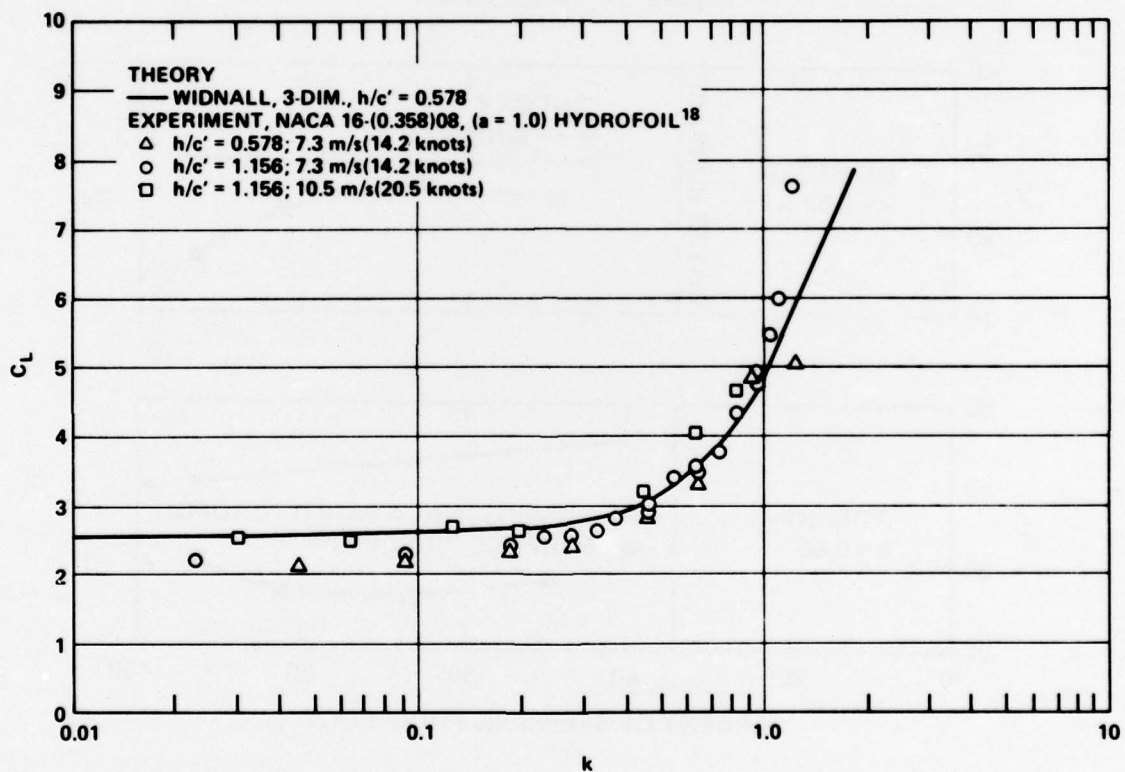


Figure 45a - Magnitude of Lift Coefficient, for Pitching
Axis at 32 Percent of the Mean Geometric Chord

Figure 45 (Continued)

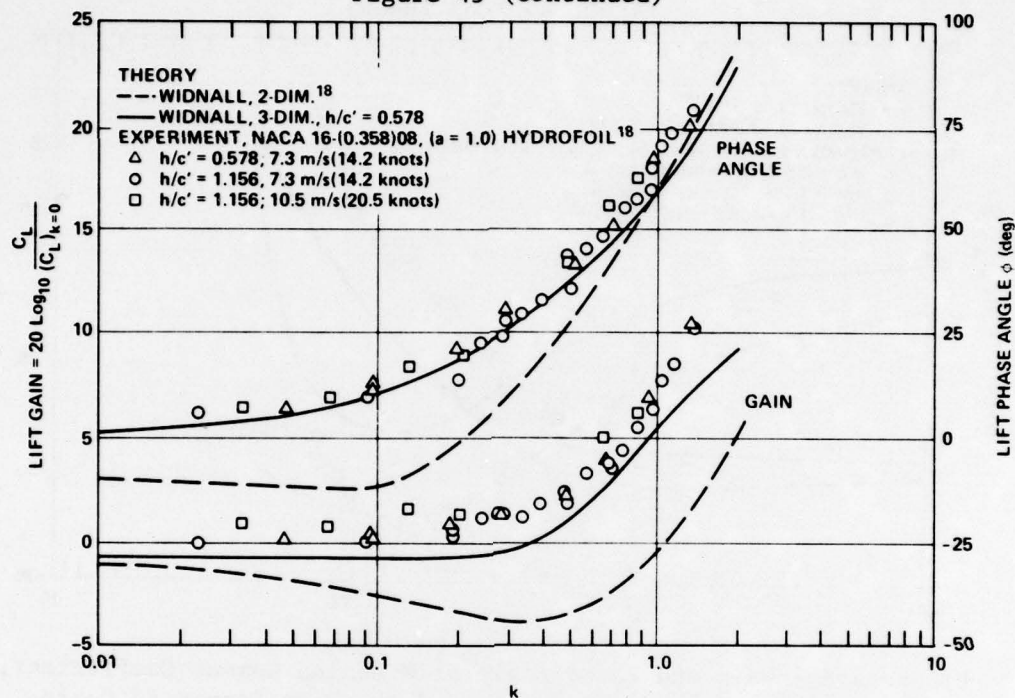


Figure 45b - Gain and Phase Angle of Lift Coefficient, for Pitching Axis at 32 Percent of the Mean Geometric Chord

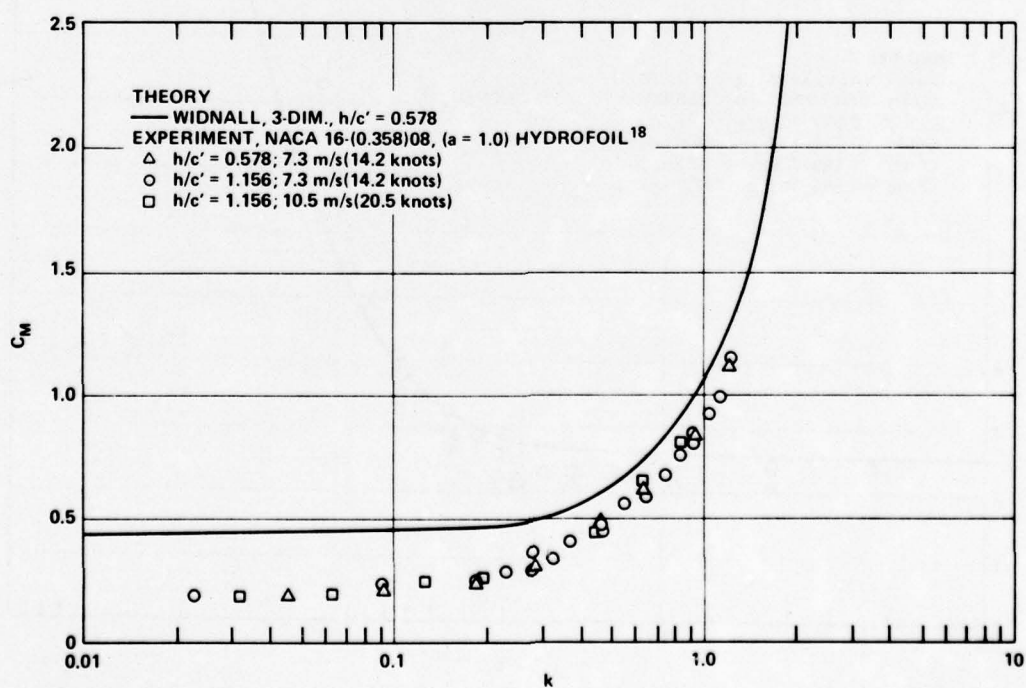


Figure 45c - Magnitude of Pitching Moment Coefficient, for Pitching Axis at 32 Percent of the Mean Geometric Chord

Figure 45 (Continued)

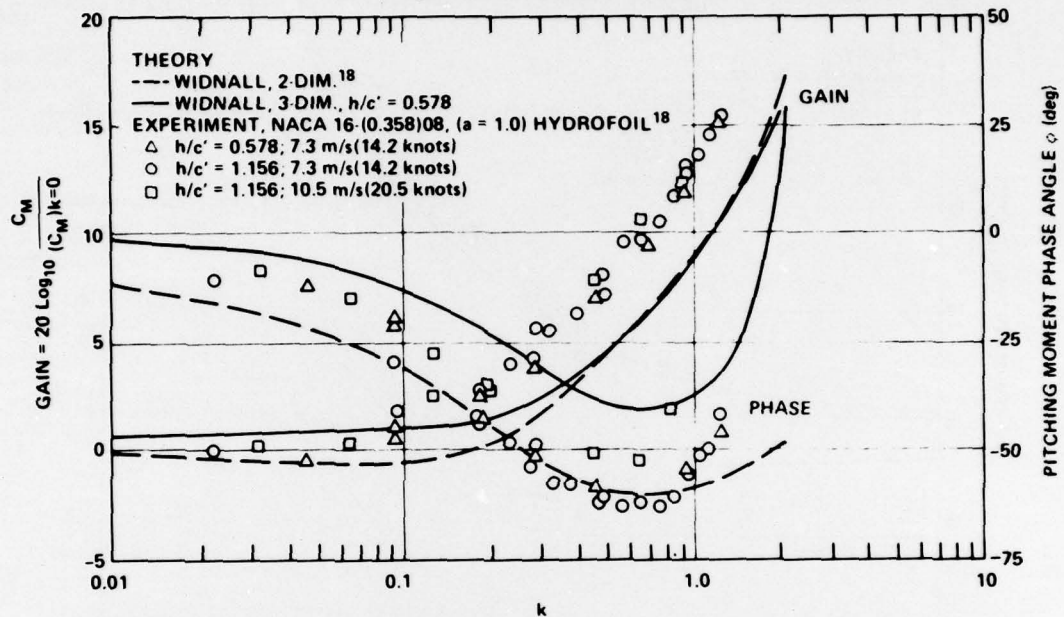


Figure 45d - Gain and Phase Angle of Pitching Moment Coefficient, for Pitching Axis at 32 Percent of the Mean Geometric Chord

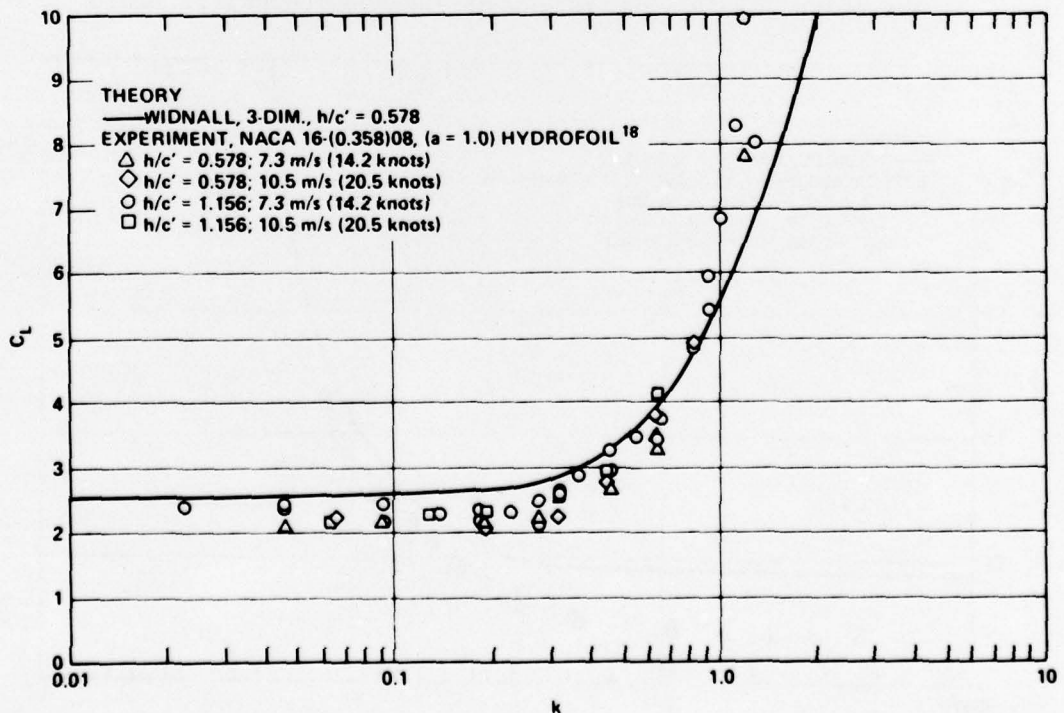


Figure 45e - Magnitude of Lift Coefficient, for Pitching Axis at 6.2 Percent of the Mean Geometric Chord

Figure 45 (Continued)

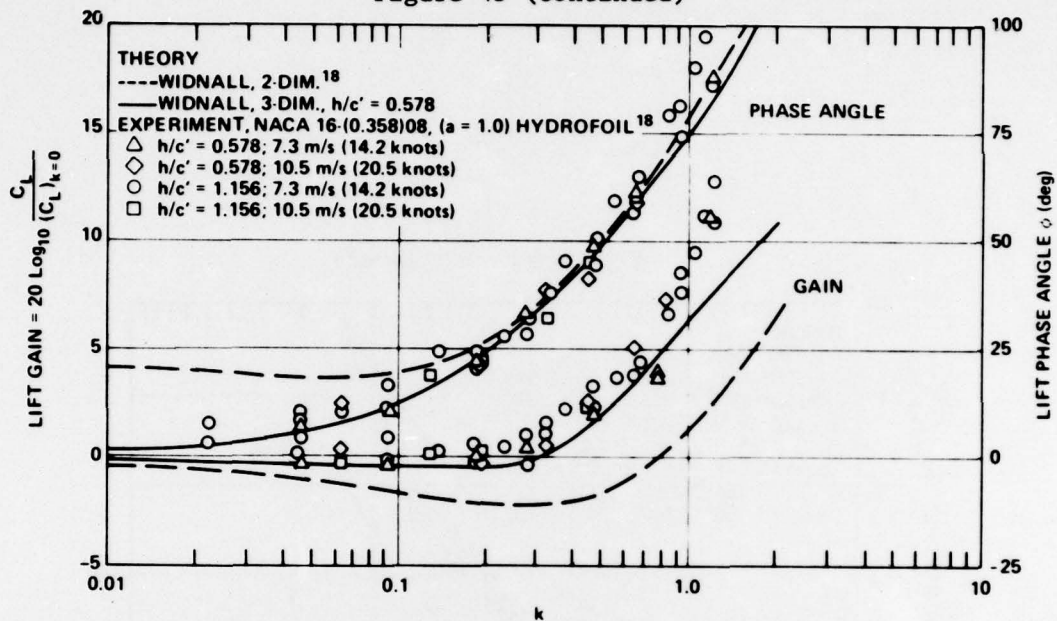


Figure 45f - Gain and Phase Angle of Lift Coefficient, for Pitching Axis at 6.2 Percent of the Mean Geometric Chord

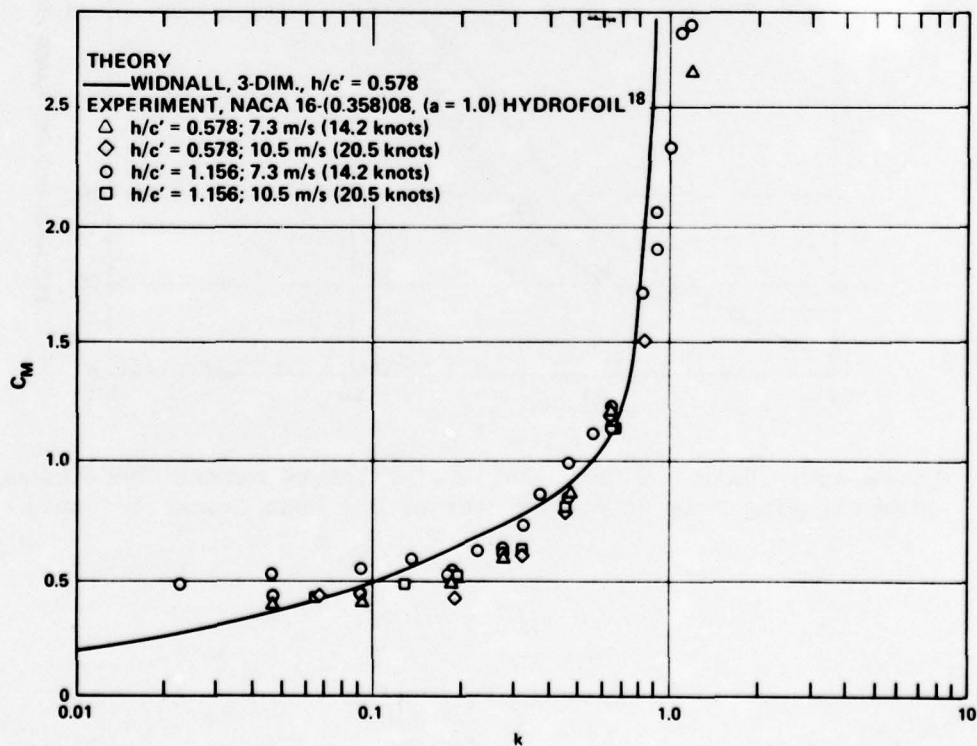


Figure 45g - Magnitude of Pitching Moment Coefficient, for Pitching Axis at 6.2 Percent of the Mean Geometric Chord

Figure 45 (Continued)

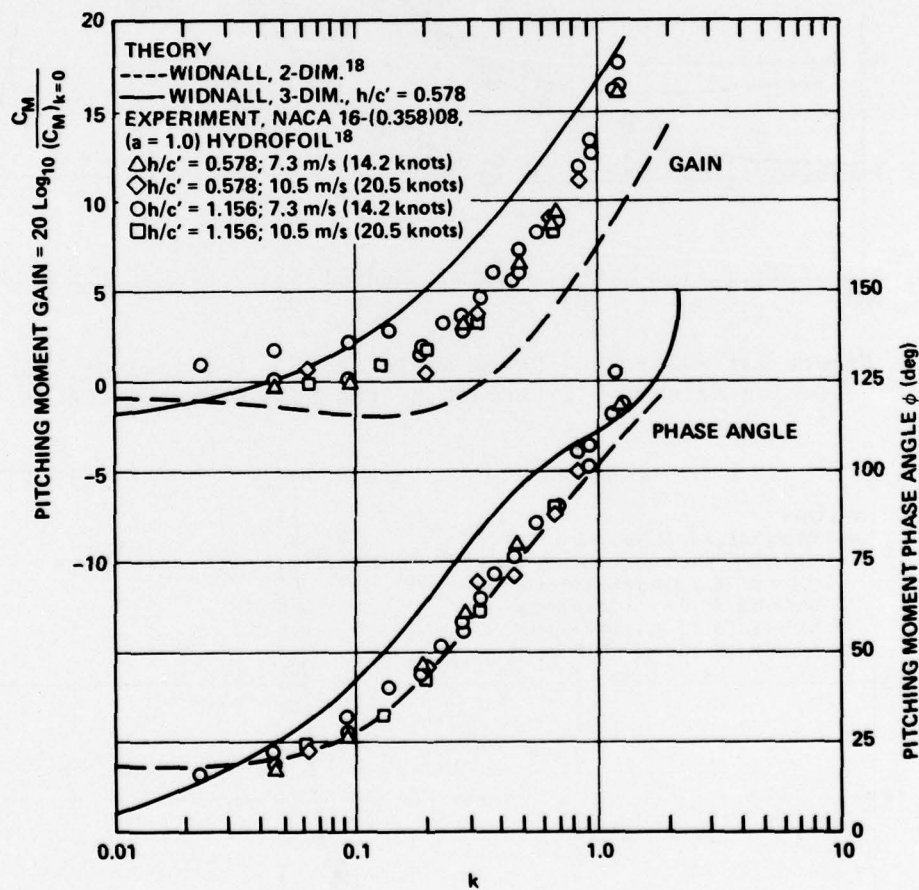


Figure 45h - Gain and Phase Angle of Pitching Moment Coefficient, for Pitching Axis at 6.2 Percent of the Mean Geometric Chord

Figure 46 - Total Unsteady Loading due to Pitching and Flapping Oscillations as a Function of Reduced Frequency for the NACA 65A010 Airfoil ($\Lambda = 0$; $\tau = 1$; $AR = 2$)

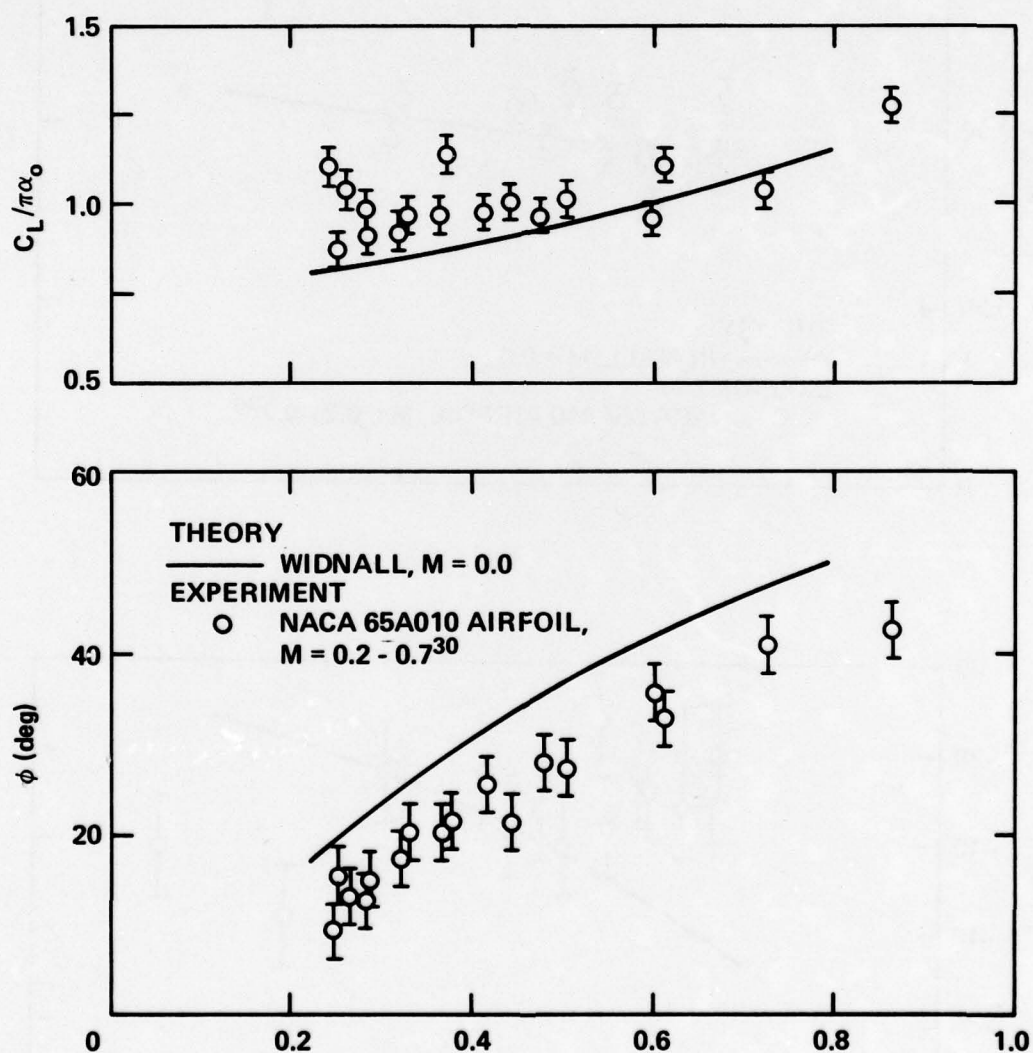


Figure 46a - Magnitude and Phase Angle of Lift Coefficient due to Pitching about Midchord

Figure 46 (Continued)

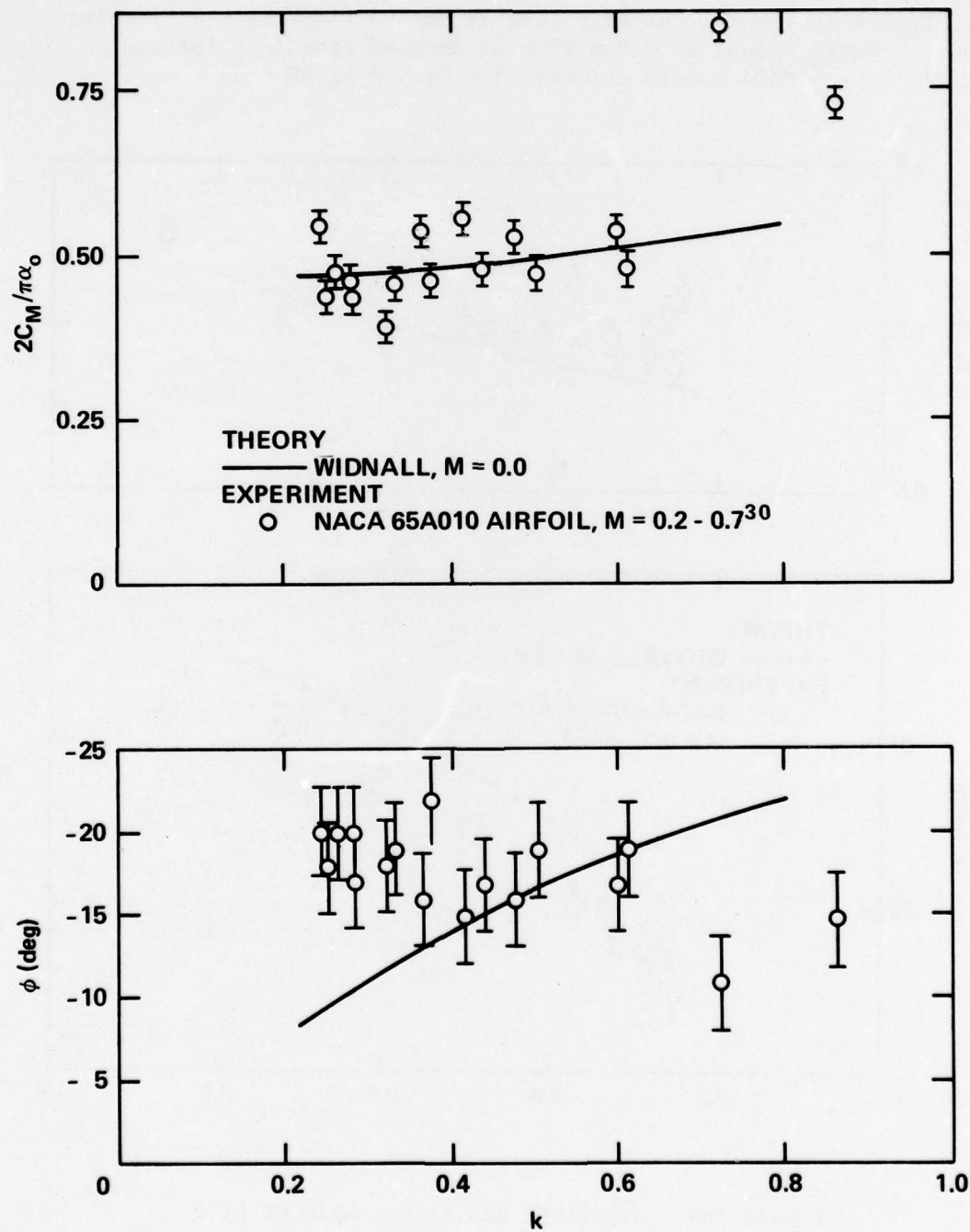


Figure 46b - Magnitude and Phase Angle of Pitching Moment Coefficient due to Pitching about Midchord

Figure 46 (Continued)

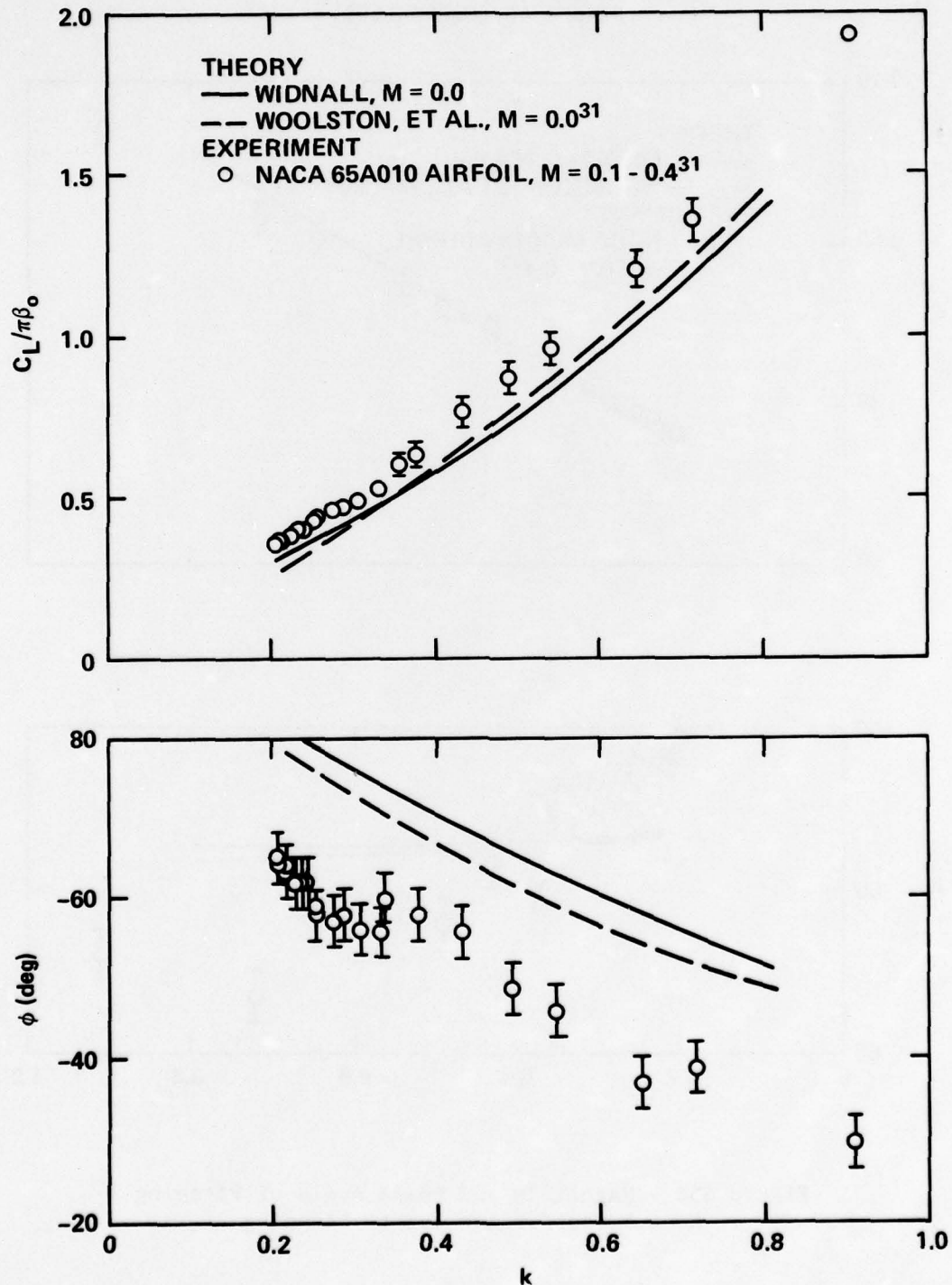


Figure 46c - Magnitude and Phase Angle of Lift Coefficient due to Flapping

Figure 46 (Continued)

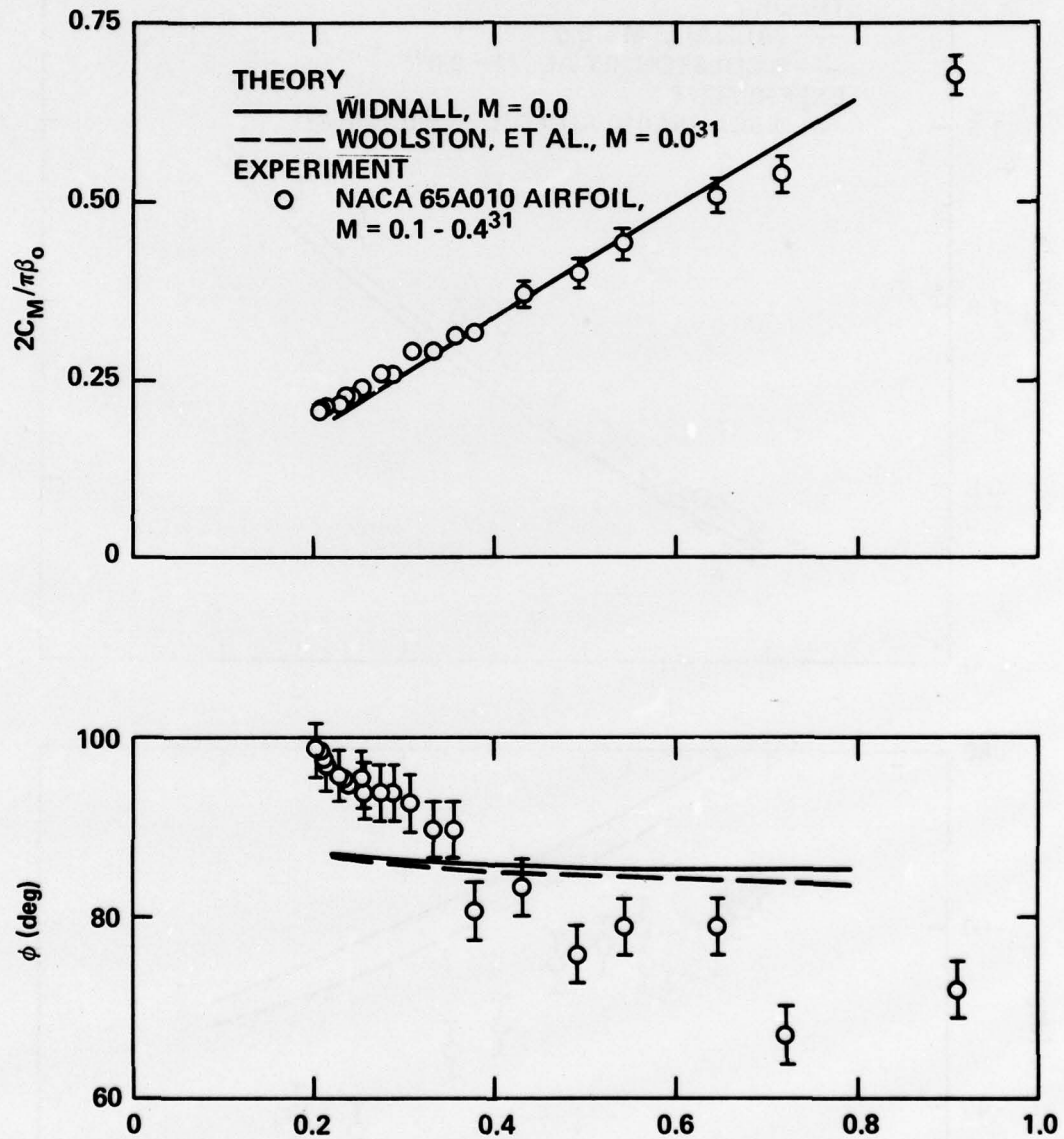


Figure 46d - Magnitude and Phase Angle of Pitching Moment Coefficient due to Flapping

Figure 46 (Continued)

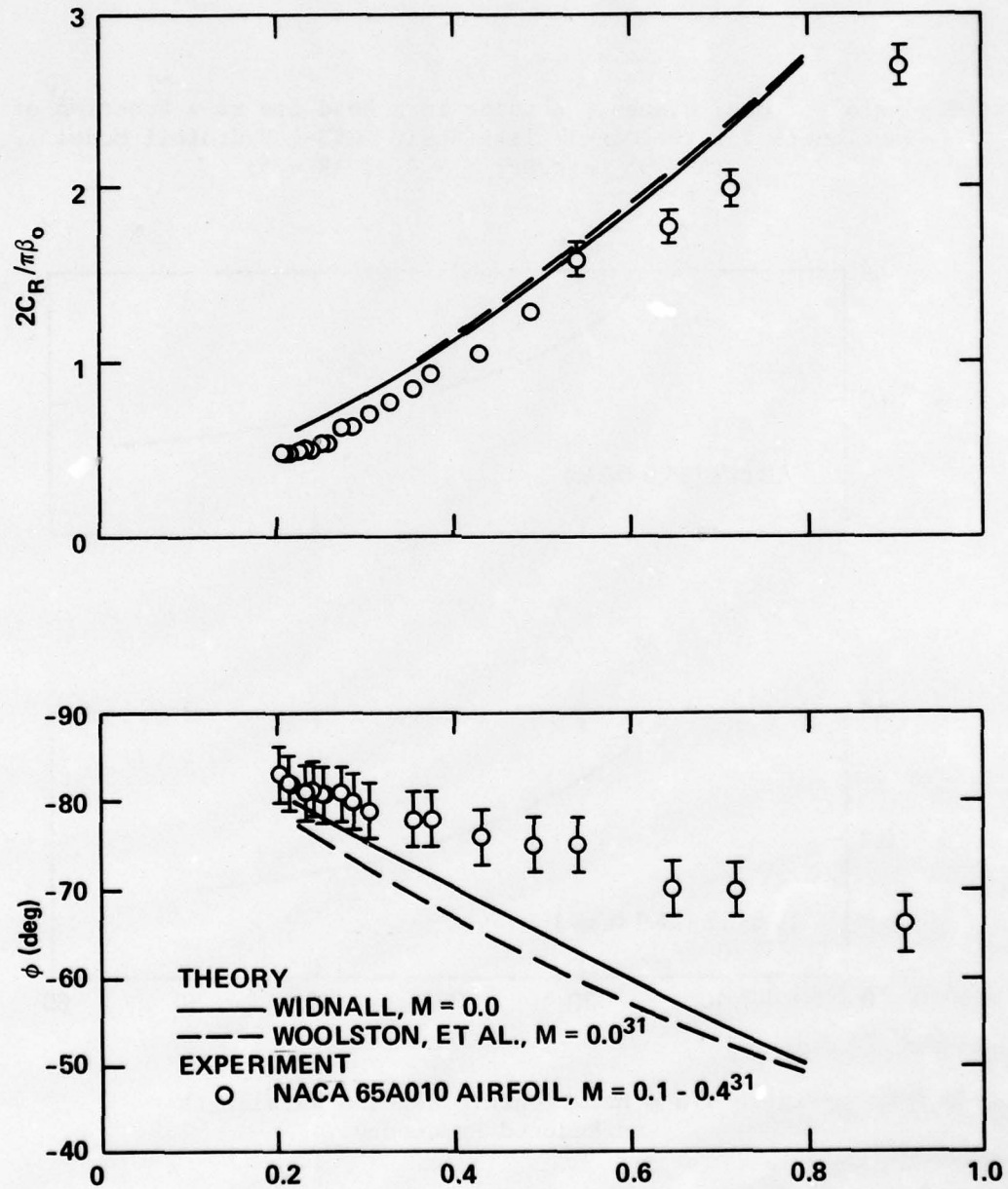


Figure 46e - Magnitude and Phase Angle of Roll Moment Coefficient due to Flapping

Figure 47 - Total Unsteady Loading in a Head Sea as a Function of Wavelength for the One-Twelfth-Scale AGEH-1 Hydrofoil Model ($\Lambda = 35$ Degrees; $\tau = 0.3$; $AR = 3$)

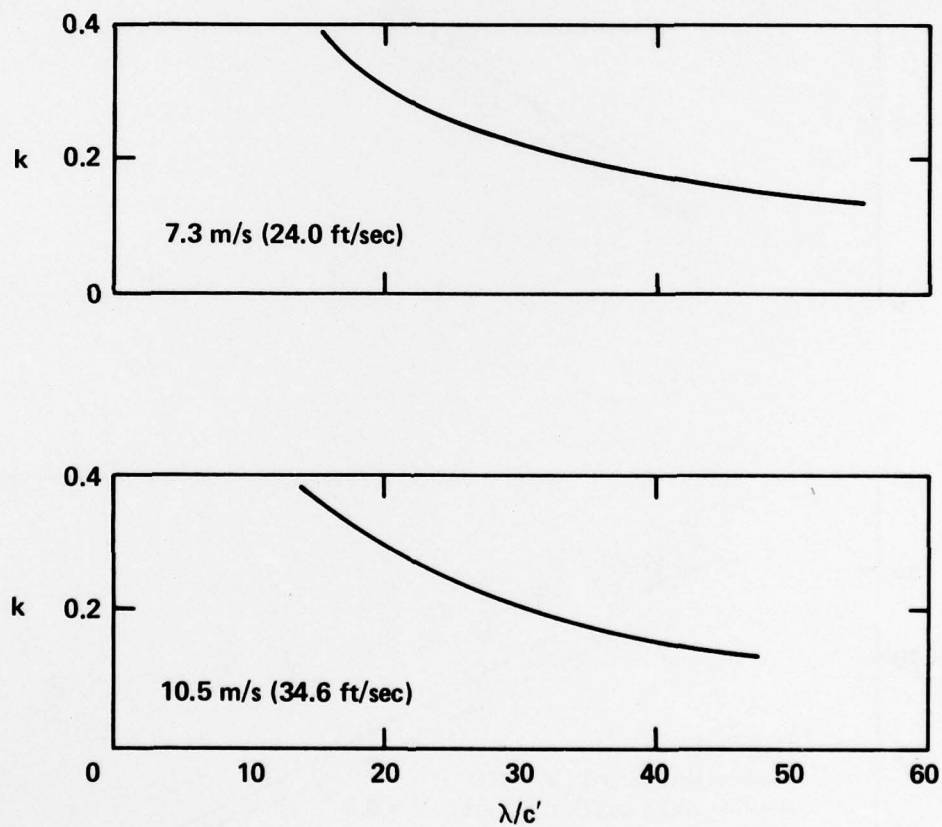


Figure 47a - Relationship between Wavelength and Reduced Frequency

Figure 47 (Continued)

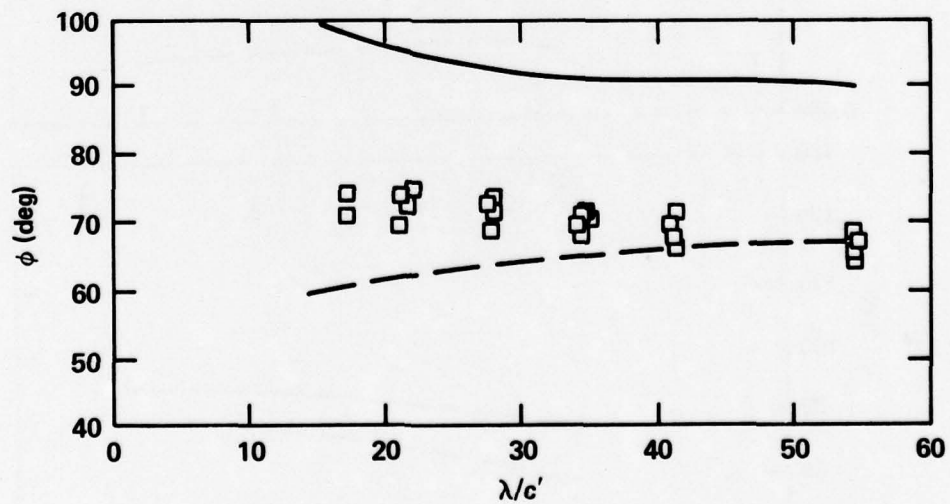
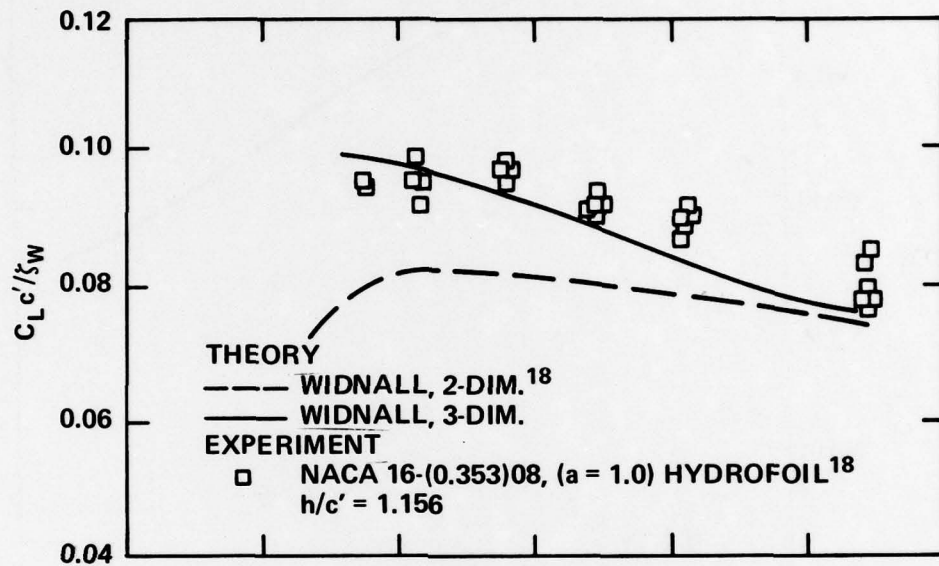


Figure 47b - Magnitude and Phase Angle of Lift Coefficient at a Speed of 7.3 m/s (24.0 ft/sec)

Figure 47 (Continued)

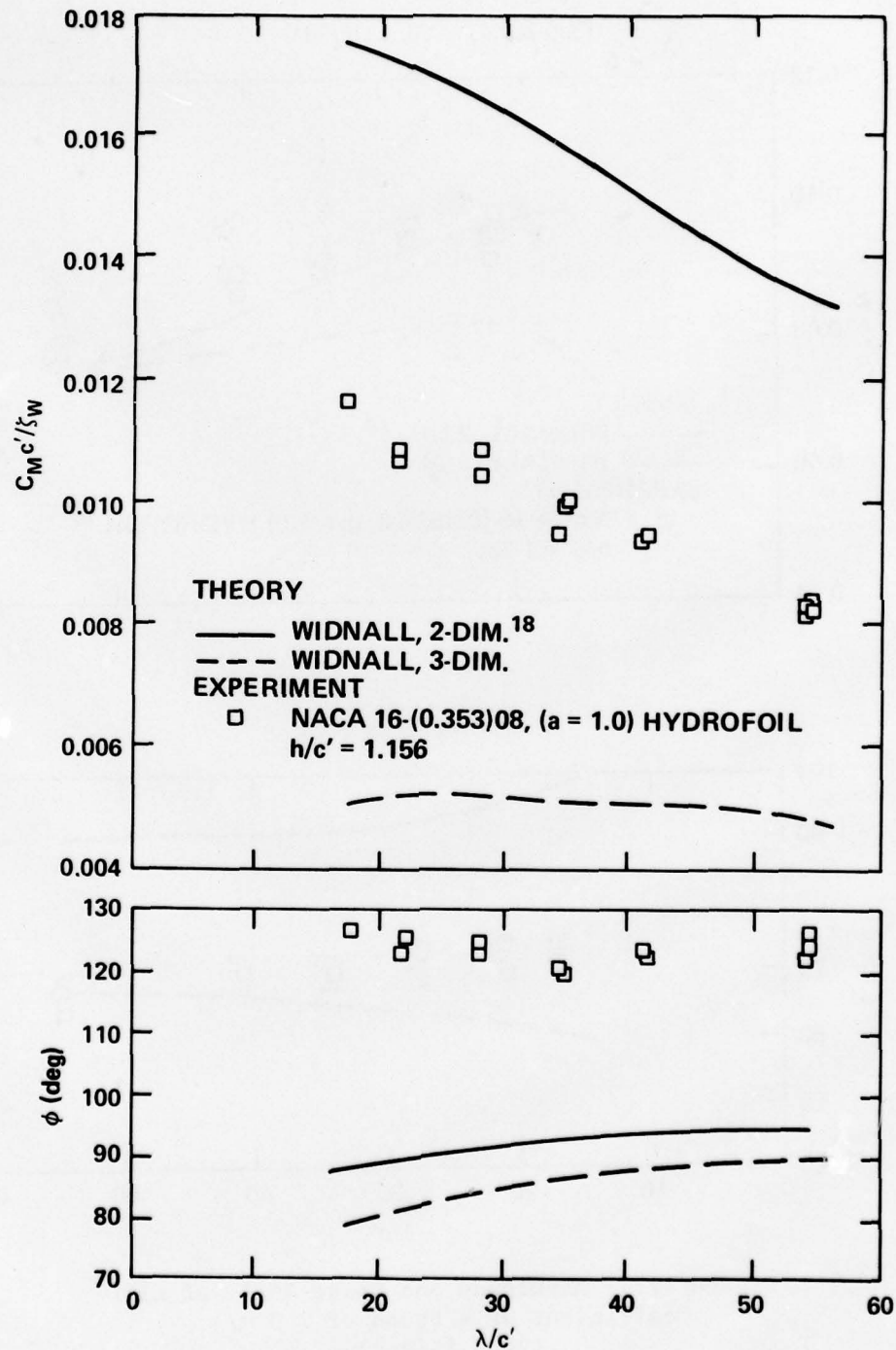


Figure 47c - Magnitude and Phase Angle of Pitching Moment Coefficient about an Axis at 32 Percent of the Mean Geometric Chord, at a Speed of 7.3 m/s (24.0 ft/sec)

Figure 47 (Continued)

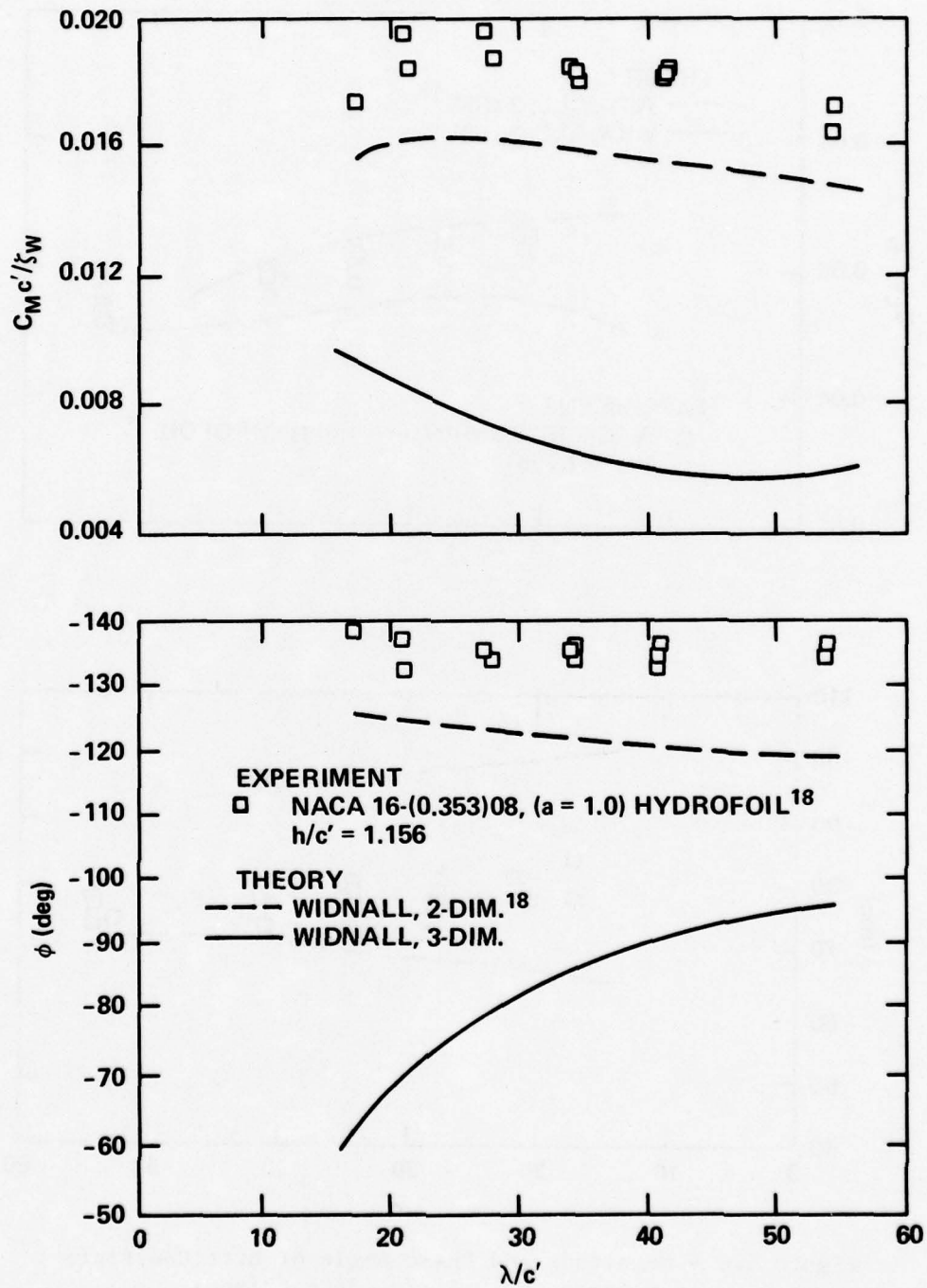


Figure 47d - Magnitude and Phase Angle of Pitching Moment Coefficient about an Axis at 6.2 Percent of the Mean Geometric Chord, at a Speed of 7.3 m/s (24.0 ft/sec)

Figure 47 (Continued)

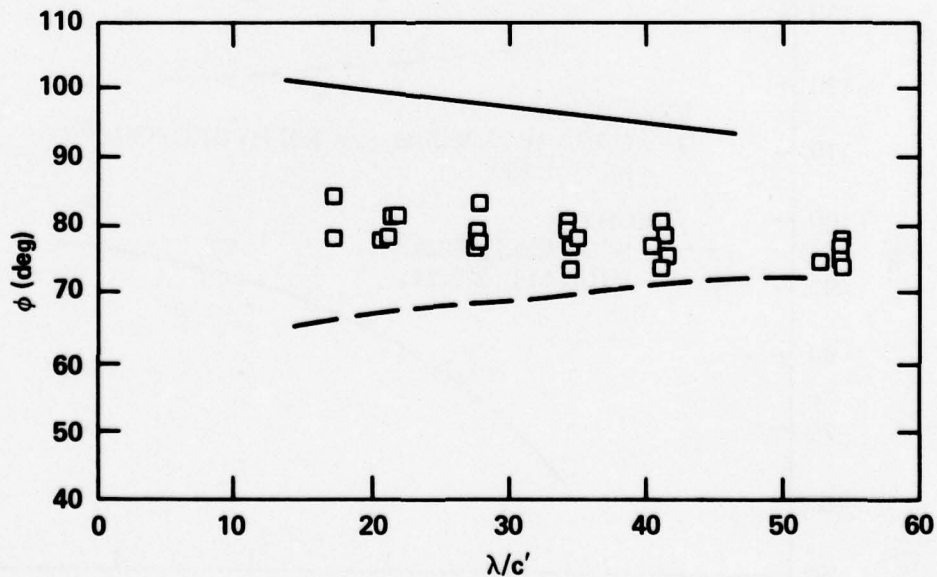
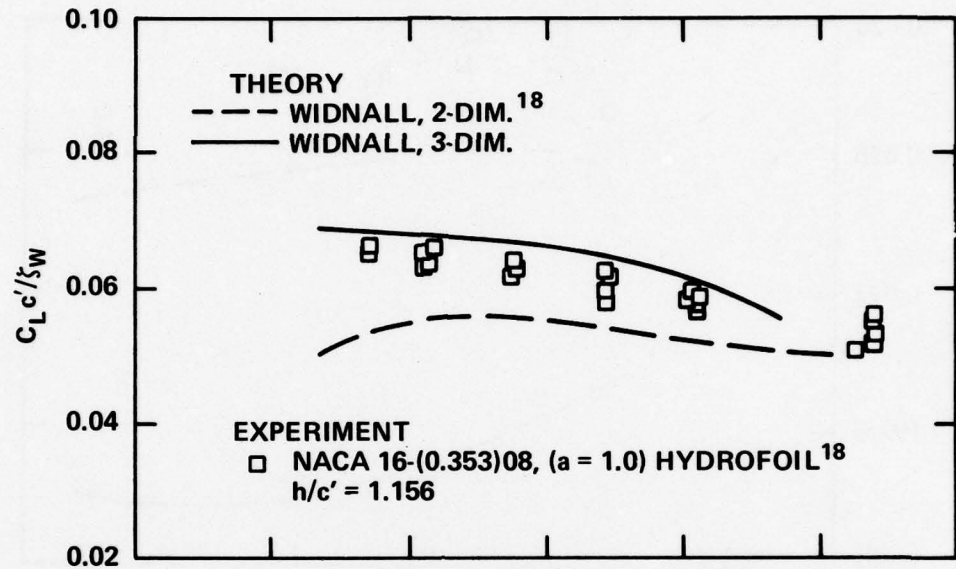


Figure 47e - Magnitude and Phase Angle of Lift Coefficient
at a Speed of 10.5 m/s (34.6 ft/sec)

Figure 47 (Continued)

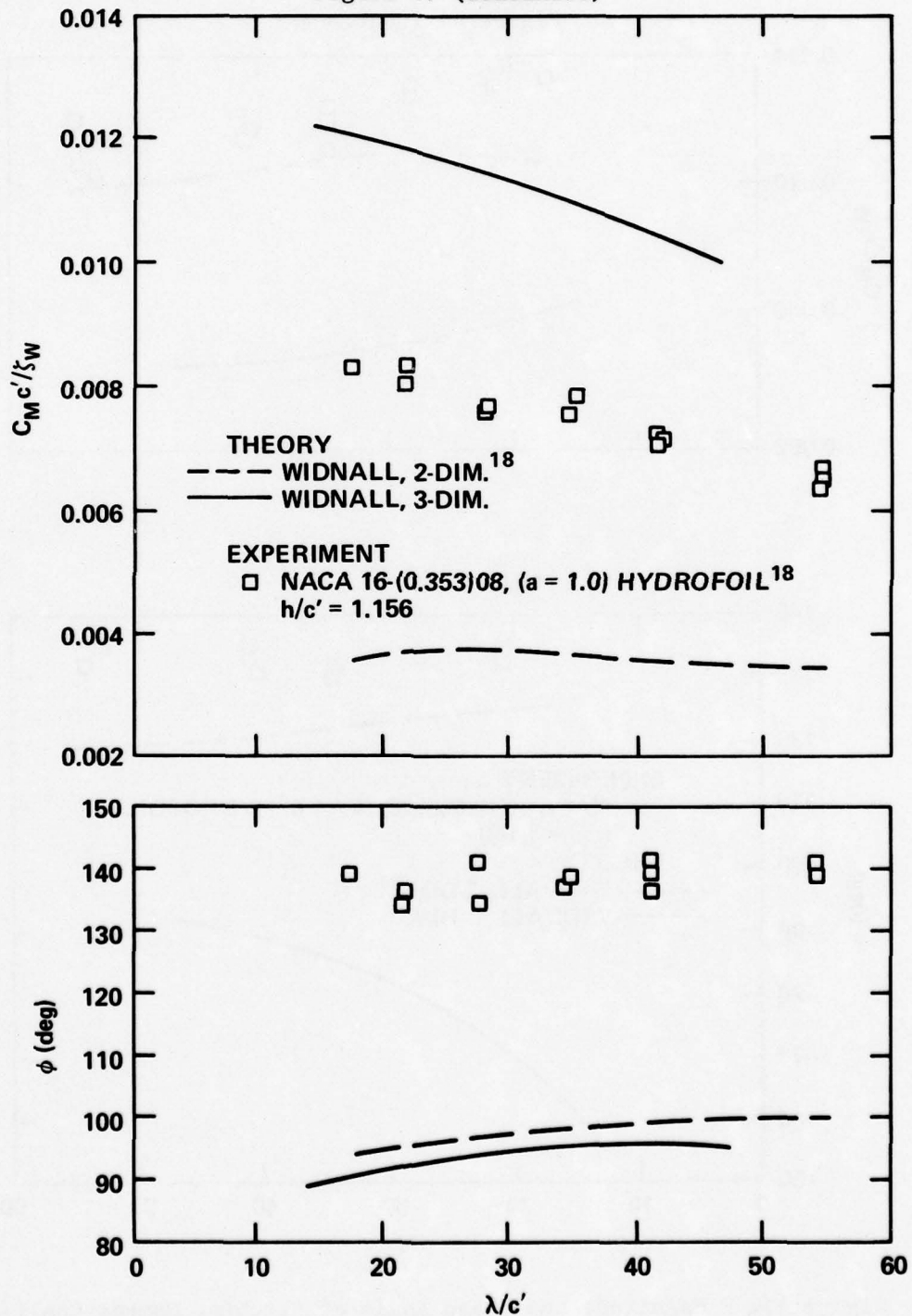


Figure 47f - Magnitude and Phase Angle of Pitching Moment Coefficient about an Axis at 32 Percent of the Mean Geometric Chord, at a Speed of 10.5 m/s (34.6 ft/sec)

Figure 47 (Continued)

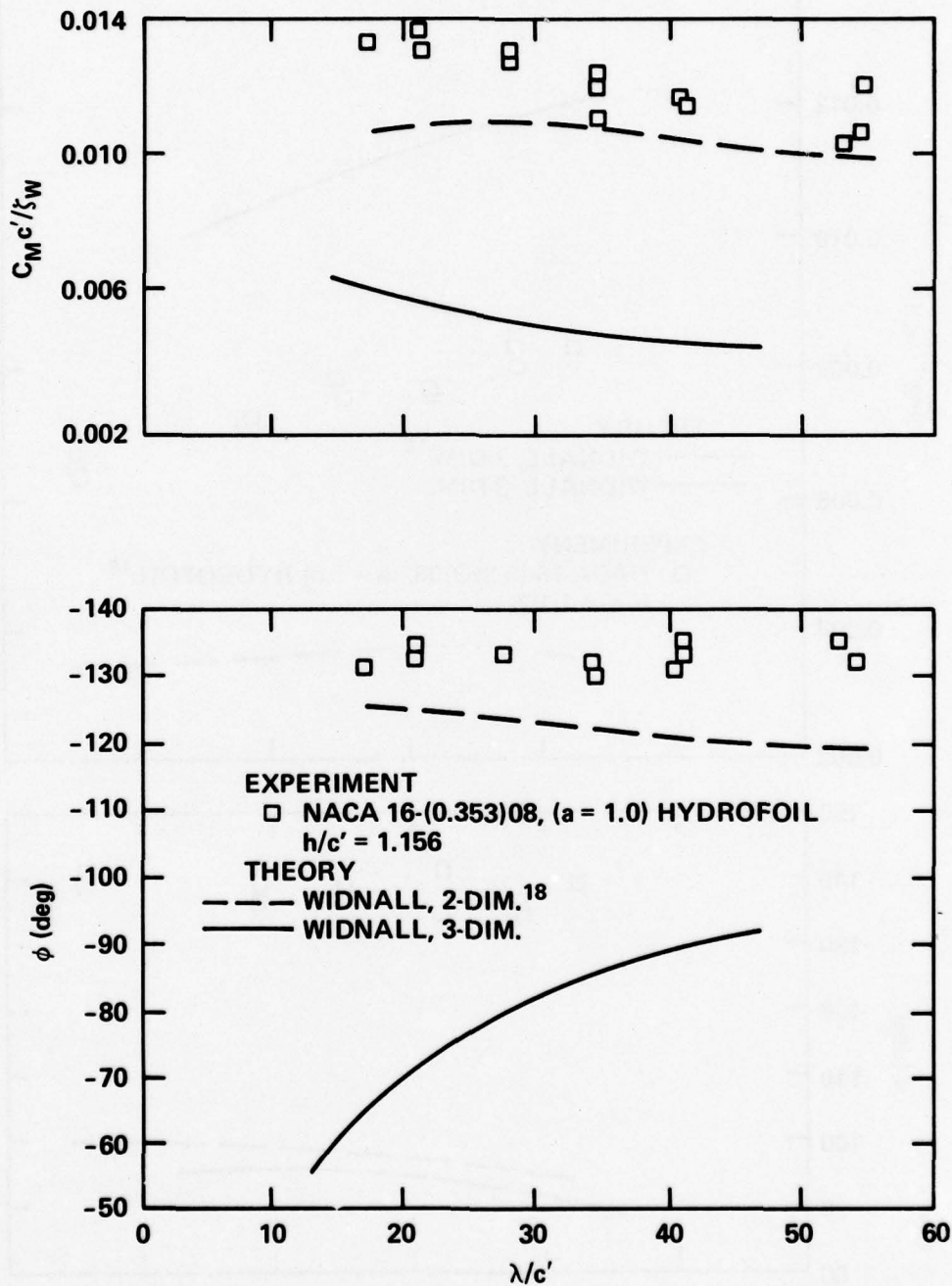


Figure 47g - Magnitude and Phase Angle of Pitching Moment Coefficient about an Axis at 6.2 Percent of the Mean Geometric Chord, at a Speed of 10.5 m/s (34.6 ft/sec)

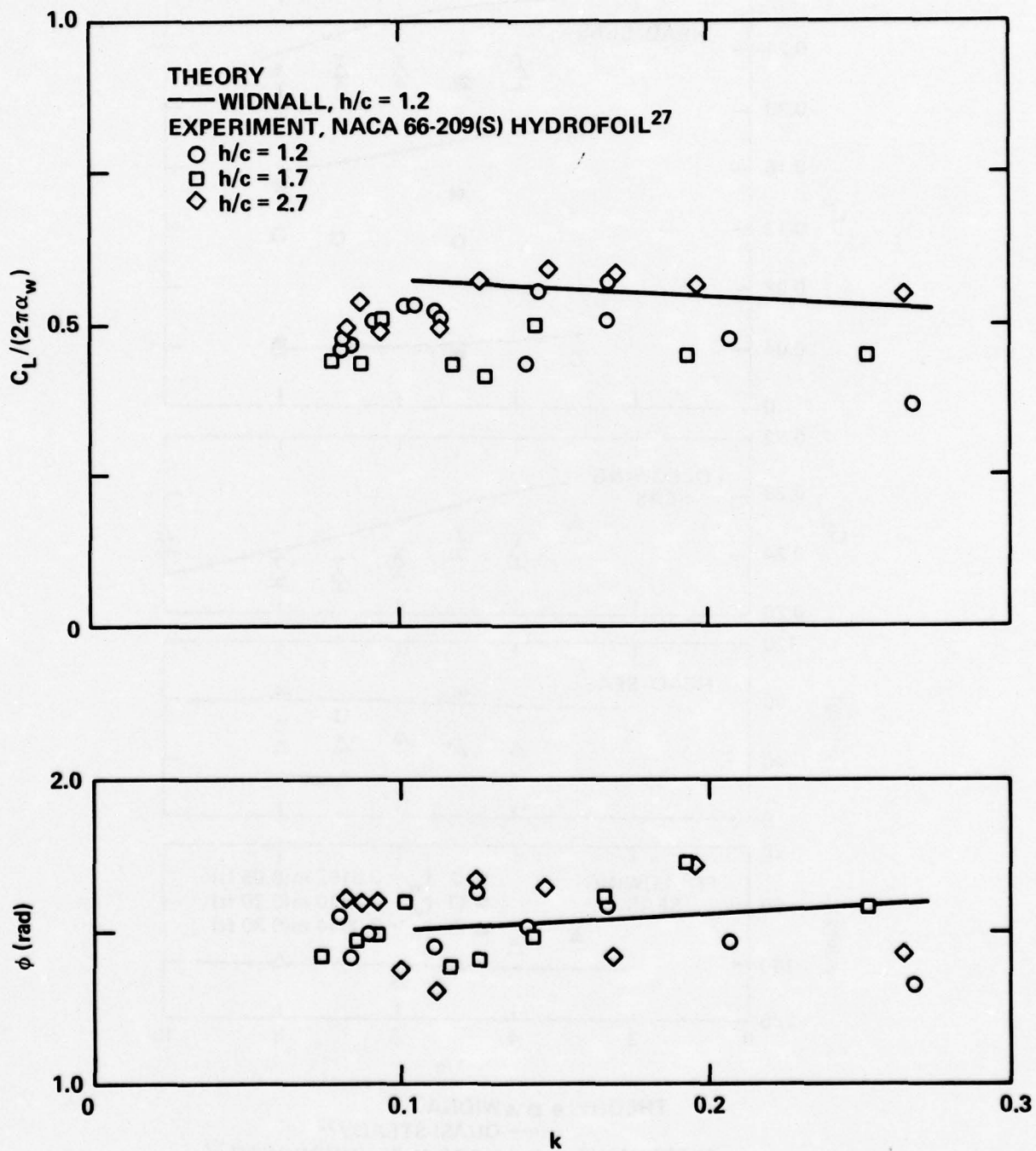


Figure 48 - Magnitude and Phase Angle of the Total Unsteady Lift in a Head Sea as a Function of Reduced Frequency for the NACA 66-209(S) Hydrofoil ($\Lambda = 0$; $\tau = 1.0$; $AR = 5$)

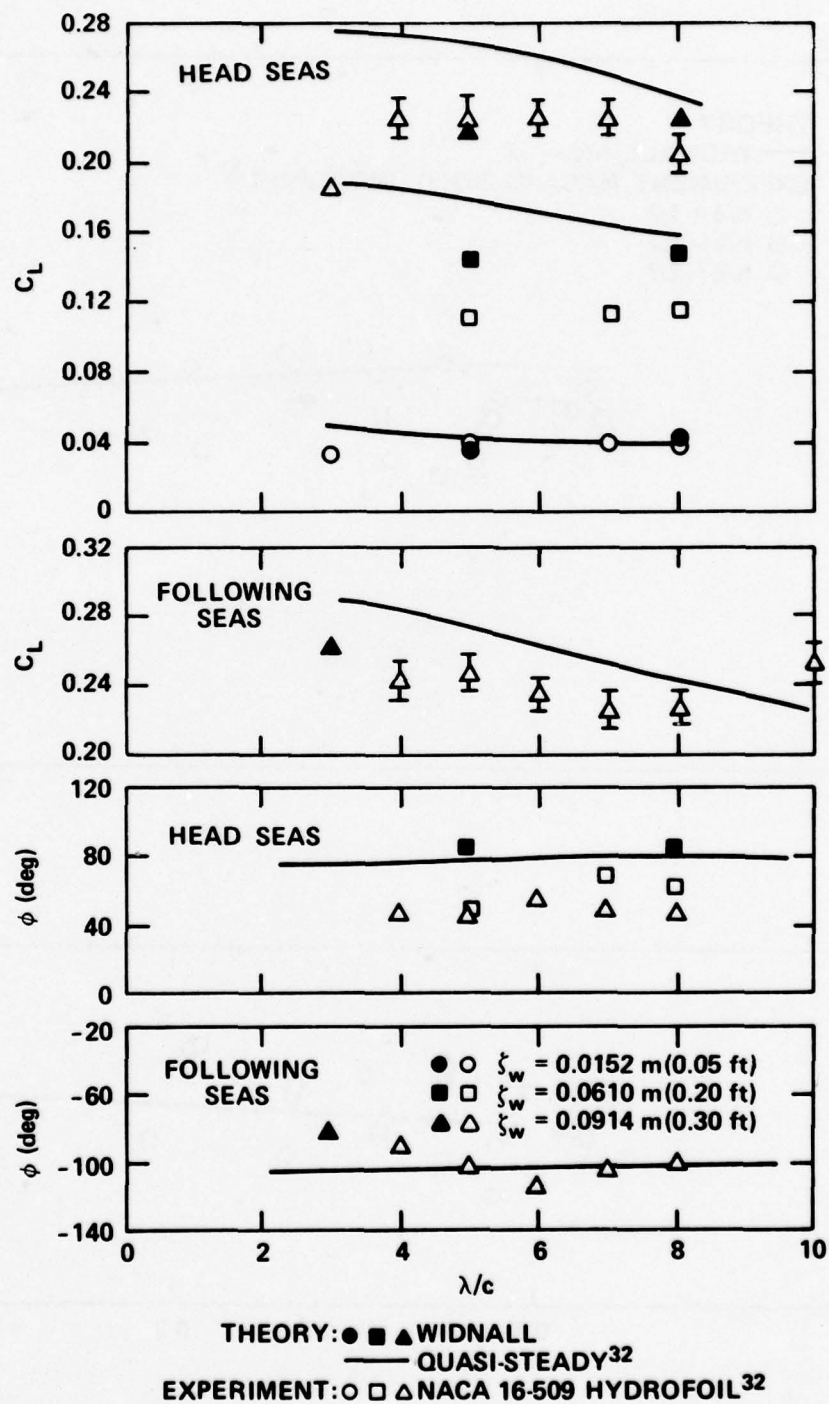


Figure 49 - Magnitude and Phase Angle of the Total Unsteady Lift in Head and Following Seas as a Function of Wavelength for the NACA 16-509 Hydrofoil ($\Lambda = 0$; $\tau = 1$; $AR = 6$)

NACA 0010 Hydrofoil and Airfoil

These models were unusual in that structural vibration modes were simulated rather than rigid-body oscillations. At the low-to-moderate values of reduced frequency for which data are available,^{15,28,29} predictions of lift were fair to good while moment predictions were fair to poor. Comparisons are shown in Figures 43 and 44. Calculated loading for the fully-submerged condition has been included even when no data were available.

A change from 0.1 to 0.5 in reduced frequency of airfoil oscillation had little effect on the accuracy of the loading calculation. The greatest discrepancy in calculated phase angle was a lead of up to 52 deg in pitching moment at $k = 0.1$. The lift magnitude ranged from 9 percent below experiment to 1 percent above experiment, while pitching moment ranged from 15 percent below experiment to 27 percent above.

In a remarkable example of experimental consistency, the fully-submerged hydrofoil data agreed fairly well with the airfoil data taken at a slightly lower reduced frequency (0.6 and 0.5, respectively). Much larger deviations characterized the comparison with the surface-piercing hydrofoil data, particularly the moment data. The lift predictions were from 27 percent below experiment to 36 percent above experiment, with phase angles up to 27 deg in error. The moment predictions ranged from 0 to 125 percent above experiment, with phase angle as much as 56 deg in error. Some of the discrepancy in the surface-piercing data due to bending was caused by a ventilated cavity which formed along the upper trailing edge of the bending model. Predictions of unsteady center of pressure x_{cp} , a quantity described in Appendix B, were from 3 percent to 16 percent of the chord aft of experimental values, as shown in Figure 44e.

AGEH-1 One-Twelfth-Scale Hydrofoil

Predicted and experimental loading on the AGEH-1 hydrofoil¹⁸ are shown in Figure 45. The loads are given both in coefficient form and as gains. The gain is a logarithmic form of load coefficient as indicated in

the figures. Because the calculated gains are given relative to calculated steady loading slopes, which did not agree with experiment, the gain does not directly indicate the accuracy of the unsteady loading predictions. In the present case, the calculated lift gain was reduced relative to experiment by this inaccuracy, while pitching moment gain was reduced for one pitching axis and increased for the other.

Lift was predicted with fair-to-good accuracy over a wide range of reduced frequency k . The prediction was 15 percent above experiment at low k and up to 33 percent below experiment for k above unity. The theory intersected the data at approximately $k = 0.75$. Lift phase angles were especially accurately predicted, with a deviation of only a few degrees in lag.

Pitching moment coefficients were not as well predicted. Accuracy ranged from 140 percent above experiment at low k to a large, indeterminate amount above experiment at high k . Smaller deviations of the opposite sign occurred at low k for one of the pitch axes. It should be understood that the prediction accuracy will, in general, vary markedly with axis location. Predicted phase angles led the experimental values by as much as 20 deg.

The two-dimensional version of the Widnall calculation¹⁸ was much less accurate in predicting the lift gain and phase than the three-dimensional calculation. The two-dimensional calculation was also, in general, less accurate in its predictions of moment magnitude, but predicted moment phase angle more accurately. In view of its overall inaccuracy, use of the two-dimensional calculation would not be justified if the three-dimensional version was available.

NACA 65A010 Airfoil

This low-aspect ratio airfoil was tested both in a pitching mode³⁰ and in a flapping mode.³¹ Comparisons between theory and experiment are shown in Figure 46.

The Widnall prediction tended to be low for lift, in good agreement with experiment for pitching moment, and high for roll moment. All calculations were within 15 percent of the average experimental values. The phase angle predictions and data varied differently with reduced frequency,

which resulted in crossover regions and in deviations as high as 17 deg. Unsteady centers of pressure were calculated within 10 percent of the chord length. The Widnall calculation was thus fairly accurate for these airfoils.

The Widnall calculations fell within a few percent of results from the Woolston lifting-surface program, and the two programs appear to be nearly equivalent.

WAVE-INDUCED LOADING

Unsteady lift magnitude and phase due to waves was predicted with accuracy similar to that obtained for oscillating foils. Lift magnitudes were up to 43 percent in error, while predicted phase angles deviated as much as 36 deg from experiment. Moment predictions were less accurate than lift predictions. The Widnall lifting-surface calculation was found to be more accurate than either a two-dimensional calculation or quasi-steady theory. Calculations and data from three models are presented in Figures 47 through 49, and are discussed further in the following sections.

AGEH-1 One-Twelfth-Scale Hydrofoil

Lift and pitching moment data were obtained for this foil in head seas over a reduced frequency range of 0.1 to 0.4.¹⁸ The Widnall two- and three-dimensional predictions are compared with experiment in Figure 47.

The prediction of lift magnitude using the Widnall three-dimensional calculation was extremely accurate, while the two-dimensional version was considerably less accurate. The three-dimensional prediction of magnitude appeared to be within experimental uncertainty of the data although phase angles were consistently 20 to 30 deg in error.

Moment predictions were poor for both calculations, with accuracies ranging from 50 percent above experiment to 60 percent below experiment. Calculated phase angles were from 70 deg above experiment to 50 deg below experiment.

It is concluded that the Widnall three-dimensional calculation is significantly more accurate than the related two-dimensional calculation in predicting lift in waves at reduced frequencies between 0.1 and 0.4.

NACA 66-209(S) Hydrofoil

Calculated and experimental lift differed by up to 43 percent for an aspect ratio 5 rectangular hydrofoil in waves,²⁷ as shown in Figure 48. More accurate predictions occurred at deeper depths. Phase angle predictions differed from experiment by as much as 16 deg, although scatter in the data suggested that the prediction may have been within experimental uncertainty.

NACA 16-509 Hydrofoil

Unsteady loading in both head seas and following seas was measured on an aspect ratio 6 rectangular hydrofoil.³² The results, corresponding to reduced frequencies between approximately 0.04 and 0.36, are shown in Figure 49. Theoretical results from the Widnall three-dimensional program and from quasi-steady theory are also shown.

The Widnall calculation was within 23 percent of experimental lift magnitude but as much as 36 deg different from measured phase angles. No significant difference occurred in the accuracy of predictions for head and following seas. As would be expected, the Widnall results became increasingly superior to quasi-steady theory as reduced frequency increased (corresponding to a decrease in wavelength λ). It is concluded that the Widnall three-dimensional calculation should be used in preference to the quasi-steady calculation at reduced frequencies greater than 0.16.

SUMMARY OF UNSTEADY LOADING PREDICTIONS

Just as for the steady loading calculation, the unsteady calculation showed a wide range of accuracy relative to the available data. The lift predictions ranged from about 30 percent below experiment to 40 percent above. Pitching moment predictions were substantially less accurate, up to 140 percent in error, although, generally, they were within about 60 percent of experiment. Predicted phase angles for lift were, as a rule, within 20 degrees of experiment; pitching moment phase angles varied much more widely.

Possibly due to the limited amount of data, no clear dependence of accuracy was found on the mode of unsteady loading (heave, pitch, or waves) or the foil aspect ratio. On the other hand, foil depth and reduced frequency did affect the accuracy. The largest deviations between theory and experiment occurred at shallow depth (Figures 42 and 44) and at both high and low reduced frequency. When lift predictions at deep submergence and moderate reduced frequency are considered, for example, the deviations reduce to less than 20 percent. Pitching moment deviations remain at a substantially higher level under these conditions. The effects of shallow submergence and high reduced frequency may be the reason for the generally superior agreement of the airfoil loading data with theory: the airfoil data did not include the extremely shallow submergences nor the high values of reduced frequency that the hydrofoil data did.

It is concluded that, as a rough approximation, unsteady lift predictions may be made with an accuracy of ± 20 percent for deeply submerged hydrofoils at reduced frequencies up to about 1.0. The predicted lift will probably be more than 20 percent above experiment at depths of one chord and less, and more than 20 percent below experiment at reduced frequencies above 1.0. A more detailed determination of the unsteady loading prediction accuracy of the Widnall program cannot be made in the absence of more systematic data.

Although no empirical correction to the unsteady predictions will be proposed, in view of the limited amount of data, it appears that a correction could be generated to account for effects of high reduced frequency. This correction, in conjunction with depth correction developed from both steady and unsteady loading data, would permit predictions to be extended to shallow submergences and higher reduced frequencies with no loss of accuracy.

DISCUSSION

The primary result of this evaluation has been to show that the Widnall program can be used to make hydrofoil lift predictions with a moderate degree of accuracy (15 to 20 percent) except at very shallow

submergences and, for unsteady loading, at very high reduced frequencies. Pitching moment predictions are much less accurate, which is not surprising in view of the dependence of pitching moment on both the magnitude and chordwise distribution of lift.

The use of an empirical correction to the steady lift predictions is of course an admission that there is some degree of inaccuracy inherent in the lifting-surface calculation. Determination of the exact amount of inaccuracy has been prevented both by residual numerical instability in the program, principally at high aspect ratio, and by a general lack of precision and scope in the body of hydrofoil data. Of particular significance for design of hydrofoil craft is the extremely limited amount of data on swept, tapered hydrofoils. For the two such planforms included in this evaluation, the predictions and the program numerical stability were both poor. This apparent deficiency must be investigated to determine whether the predictions or the model test results are in error.

Some of the findings concerning the NACA $a = 1.0$ mean line suggest that other choices of mean line would be preferable. Experimental results show that the sectional lift on this mean line is only about three-quarters of the theoretical value, while other profiles realize approximately the full theoretical value. Furthermore, a modal approach to describing chordwise pressure distributions cannot successfully represent this type of camber lift. As a result, certain types of calculation such as estimating cavitation inception are impossible. If a camber line which produces less abrupt increases in pressure near the leading and trailing edges can meet the design requirements, more accurate predictions would probably be available from the Widnall program for optimizing other design parameters.

CONCLUSIONS

1. The Widnall program can be used, in conjunction with an empirical correction, to predict hydrofoil lift with a moderate degree of accuracy (15 to 20 percent) except at very shallow submergences and very high reduced frequencies. Further empirical corrections for these parameter ranges can be derived from the available data.

2. Establishment of a higher prediction accuracy may be possible but is now prevented by lack of sufficient high-quality hydrofoil loading data and by some residual numerical instability in the calculation.

3. The Widnall lifting-surface program is preferable as a design tool to the Bandler program, the Widnall two-dimensional program, and a quasi-steady theory for reasons of accuracy or numerical stability.

4. Hydrofoil model data suffer widely from unreported experimental error. The principal source of error is the angle of attack measurement. Some models may also experience a shift in transition which results in an inaccurate camber lift measurement. Model profiles may also be incorrect unless proven otherwise by measurement.

RECOMMENDATIONS

1. Improved-quality measurements of hydrofoil loading should be made to permit more precise determination of the accuracy of the Widnall and other calculations. Particular care should be taken to obtain accurate camber lift data, by assuring accurate measurements of angle of attack, correct model profiles, and using transition stimulation or flow visualization to avoid wrongly scaled transition behavior. Swept, tapered hydrofoils with and without pods should be emphasized.

2. The numerical aspects of the Widnall program should be investigated to eliminate numerical instabilities.

3. The Bandler lifting-surface computer program should be numerically extended to allow determination of its numerical stability and accuracy.

APPENDIX A
DESCRIPTION OF EXPERIMENTAL MODELS

HYDROFOIL AND AIRFOIL MODELS IN STEADY MOTION

Most of the steady loading data used in the present study were obtained from measurements on hydrofoils. In all, some twenty-one different model configurations were represented. The largest systematic body of data pertained to the DTMB Series HF-1 family of rectangular hydrofoils.⁸ These foils had 0.229-m (9-in.) chords and NACA 16-309, $a = 1.0$ profiles. Aspect ratios of 1, 2, 3, 4, 6, and 8 were investigated. The experimental data were converted from the originally published normal and longitudinal force coefficients to lift coefficients for the present comparison. Experimental uncertainty in the foil angle of attack α was substantial, amounting to at least ± 0.5 deg according to internal comparisons among the data. Estimates of uncertainty in $C_L(\alpha = 0)$ were obtained by multiplying nominal values of lift slope $C_{L\alpha}$ by the uncertainty in α . The accuracy of angle of attack changes was not reported, so that uncertainty in $C_{L\alpha}$ could not be determined. Load measurements are plotted in Figures 34 and 35.

A second group of data pertained to three $AR = 6$ rectangular hydrofoils, two with NACA 16-509 and 16-1009, $a = 1.0$ profiles and one with a NACA 23012 section.¹³ The foils had 0.128-m (5.0-in.) chords. In the original reference, variations in lift coefficient as a function of speed were presented. Essentially constant values of lift coefficient occurred below the speeds at which cavitation appeared; these constant values were used in the present work. Uncertainty in foil angle of attack was reported as $+0.2$ to -0.3 deg. Error bands for $C_L(\alpha = 0)$ were calculated using nominal values of $C_{L\alpha}$, but could not be calculated for $C_{L\alpha}$ itself because the range of uncertainty for lift was not given. Data are plotted in Figures 34g and 35f.

An additional group of data included five rectangular hydrofoils of varying design. One was an uncambered plate with an elliptical nose and a bevelled trailing edge.⁹ It had a 0.180-m (7.07-in.) chord and an aspect ratio of 1. The error in the lift slope data for this foil is indicated

in Figure 35a for a 6.10 m/s (20 ft/sec) condition; the range of experimental uncertainty in $C_L(\alpha = 0)$ is included within the data symbol in Figure 34a. The second and third foils, of 0.204-m (8-in.) chord length, had NACA 64₁A412, $a = 1.0$ profiles and aspect ratios of 4¹⁰ and 10;¹⁴ see Figures 34d, 34i, 35d, and 35h. Data given in Reference 10 had been corrected for tare loading and angular deflection of the dynamometer, but the range of uncertainty was not given. The fourth and fifth foils had aspect ratios of 5.0¹¹ and 5.84;¹² see Figures 34e, 34f, and 35e. The AR = 5 foil had a 0.100-m (3.9-in.) chord and a NACA 66-209(S) profile. The (S) indicated a "slight" change in the lower offsets near the trailing edge. Only one value of angle of attack was used, and, consequently, no values of $C_{L\alpha}$ were obtained. The AR = 5.84 foil had a 0.120-m (4.7-in.) chord and a circular segment profile (flat lower surface, convex upper surface) of 7.5-percent maximum thickness. No values of uncertainty were reported for the latter two foils.

Data from segmented hydrofoils with simulated bending and torsional deflections¹⁵ were also used. The rectangular foils had 0.457-m (18-in.) chords and NACA 0010 profiles. An effective aspect ratio of 5 and an effectively infinite depth were produced by a large endplate, which was parallel to the free surface and perpendicular to the hydrofoil span. Dynamometers at five spanwise locations enabled spanwise distributions of loading to be measured. The two versions of the foil were mechanically deflected to produce bending and torsional deflections, respectively, in both steady and unsteady modes. Error flags shown in Figure 36 correspond to the reported ± 0.2 deg uncertainty in angle of attack.

Published loading data were available for only two swept, tapered hydrofoil models. One was a 1/12-scale model of the AGEH-1 (PLAINVIEW) main T-foil.¹⁷⁻²⁰ The load-bearing foil on the model had a sweep angle $\Lambda = 35.2$ deg, a taper ratio $\tau = 0.3$, and a mean chord $c = 0.220$ m (8.65 in.). Data are plotted in Figure 38. The foil had a NACA 16-(0.353)08, $a = 1.0$ profile defined normal to the 32-percent chord line,¹⁸ necessitating calculation of streamwise section characteristics for use in the computer calculations. The section offsets were inadvertently calculated

for a 25-percent chord reference line, but the difference is believed to be negligible. The relatively large model pod was not considered in the calculation. The foil was rotated in pitch about several different axes, as indicated in the figure.

The second swept, tapered foil was a 1/8-scale model of the forward T-foil on the PCH-1 (HIGH POINT) hydrofoil craft. This foil is designated as Model A in Reference 16. It had $\Lambda = 15$ deg, $\tau = 0.35$, $AR = 6.1$, and $c = 0.150$ m (5.9 in.). Data are shown in Figure 37. The profile was a NACA 16-309, $a = 1.0$ section defined in the streamwise direction. No range of experimental uncertainty was reported for either of the swept, tapered models.

Four sets of measurements^{21,25*} on a commonly-used hydrofoil section, the NACA 16-309 ($a = 1.0$) profile, in two-dimensional flow were also included to represent infinite aspect ratio. Two of the studies were done with hydrofoil models, and two with airfoil models. One hydrofoil model had a 0.15-m (6-in.) chord length and was tested in the two-dimensional test section of a water tunnel. Airfoils of 0.127-m (5-in.)²⁵ and 0.762-m (30-in.)* chord were tested in wind tunnels. Experimental uncertainties were not given. Data for one of the airfoils and the hydrofoil are compared in Figure 39. The second hydrofoil²¹ had a 0.15-m (6-in.) chord and was towed beneath the free surface of a towing basin; data are shown in Figure 40. Struts of 0.4-m (15.7-in.) chord were placed at each end of the foil to approximate two-dimensional flow.

HYDROFOIL AND AIRFOIL MODELS IN UNSTEADY MOTION

NACA 66-209(S) Hydrofoil

This model has been previously described in the preceding section as a source of steady loading data. It was tested²⁷ in a rigid heaving mode at a model speed of 6.1 m/s (20 ft/sec) and a fixed angle of attack of 1.8 deg. Results are shown in Figure 42. The lift coefficient used in Reference 27 was not fully defined and was here assumed to be $C_L c' / (2\pi\delta_o)$ where δ_o is the amplitude of the heave motion.

*Also, informal communication (Jun 1978) with E. A. Jones of the Canadian Defence Research Establishment Atlantic.

Unsteady loading was also measured for this foil in waves,²⁷ again at a 1.8-deg angle of attack; see Figure 48. The lift data in waves were inferred to have been reported in the form $C_L/2\pi\alpha_w$, where α_w was the amplitude of the effective unsteady angle of attack due to the waves. No experimental uncertainty values were given.

NACA 0010 Hydrofoil

This category includes the two segmented models also used for steady load measurements. Foil motions were produced by oscillating the tips of the foils in translation and rotation, resulting in spanwise mode shapes approximating the first bending and first torsion modes of a cantilever beam. The axis of torsional oscillation was at the quarter-chord line. A large end plate doubled the aspect ratio when the foil was fully submerged. Pitching moments were reported about an axis at 31 percent of the chord.

The models were tested at both full submergence^{15,29} and at 65-percent submergence.²⁹ At 65-percent submergence, the foil should be referred to as a vertical surface-piercing strut.

Although these foils were tested at several values of reduced frequency, dynamometer inaccuracy caused all data except that below $k = 0.67$ to be unreliable. As a result, unsteady data are available only at $k = 0.6$; see Figure 44. The range of uncertainty in these remaining data was not reported.

NACA 0010 Airfoil

Because no unsteady data were available from the flexible hydrofoil models mentioned above at low reduced frequencies, data from two very similar, uncambered NACA 0010 profile airfoils²⁸ have been included in this study. The data were obtained for both bending and torsional oscillations. Although similar in size to the hydrofoil model, the airfoil model was oscillated about the 35-percent chord line during torsional oscillations, and moments were reported about this axis. Unsteady data at the lowest reduced frequency, 0.1, and highest reduced frequency, 0.5, were

used for comparison with theory. These data are presented in Figure 43. While no range of uncertainty was given, the data are believed to be of good accuracy.

AGEH-1 One-Twelfth-Scale Hydrofoil

The third hydrofoil configuration was a 1/12-scale model of the AGEH-1 main strut-pod-foil system. This model was described in the preceding section on steady loading.

One type of unsteady loading was obtained¹⁸ by oscillating the foil in pitch about either of two axes at reduced frequencies k up to 2. The axes were located at 5.94 and 31.94 percent of c' , measured aft of the leading edge.¹⁹ These locations correspond to 47 and 64 percent of the root chord from the leading edge. In each case, the lift and the pitching moment at the axis were measured. The experimental procedure did not compensate for inertial effects of the foil and linkage. Therefore, the authors weighed and measured the model, which was available and intact, and calculated inertial corrections to the experimental data published in Reference 18. These corrections were not negligible, but did not greatly alter the published data. The corrected data, shown in Figure 45, were used in this report.

Foil loading was also measured¹⁸ in head seas at a depth of 0.25 m (10 in.) for speeds of 7.3 and 10.5 m/s (24.0 and 34.6 ft/sec). The waves had 0.10-, 0.15-, and 0.25-m (4-, 6-, and 10-in.) peak-to-peak amplitudes ζ_w and 3.8- to 12.2-m (12.5- to 40-ft) wavelengths λ , although not all possible combinations of amplitude and wavelength were used. The steady angle of attack was 1.4 deg at the lower speed and -1.5 deg at the higher speed. Measured loading values are given in Figure 47. The downwash used in the loading prediction included both the horizontal and the vertical components of orbital velocity.³³ It was assumed that the depth of the water was greater than one-half the wavelength. Since the towing basin used for the experiment was 4.9 m (16 ft) in depth, this assumption was invalid for wavelengths longer than 9.8 m (32 ft).

The experimental uncertainty in the measured loading was not given for this model.

NACA 16-509 Hydrofoil

The remaining wave-loading data were obtained from an $AR = 6$ rectangular foil with a NACA 16-509, $a = 1.0$ profile.³² The foil was experimentally tested at a depth of one chord (76 mm or 0.25 ft) and an angle of attack of 4 deg in both head seas and following seas. Computer predictions for the lift were compared with experimental results for a model speed of 3.1 m/s (10 ft/sec); see Figure 49. The computer predictions were made only for $\lambda = 1.5$ and 2.4 m (5 and 8 ft) in head seas and for $\lambda = 0.9$ m (3 ft) in following seas. The values of k were calculated using a calculated wave propagation speed. In head seas, k varied from 0.365 to 0.161 as λ increased; in following seas, the variation was from 0.159 to 0.035. The plot of lift phase versus wavelength for the following seas which appears in Reference 32 is inconsistent in the labeling of the ordinate ϕ . Thus the experimental phase is unknown within 40 deg. The labeling used in this report assumes that the phase due to following seas is approximately 180 deg greater than that due to head seas. Since the phase associated with head seas was correctly plotted, it was determined that the experimental phase due to following seas clustered around -100 deg and not around -60 deg. Dynamometer response limitations produced an uncertainty of ± 5 percent in lift amplitude and ± 5 deg in phase angle.

NACA 65A010 Rectangular Airfoil

The second airfoil model had an $AR = 2$ rectangular planform with a NACA 65A010 profile.^{30,31} The chord length of the foil was 0.305 m (12 in.). A rigid semispan model of the foil was oscillated in pitching³⁰ and flapping³¹ modes at Mach numbers from 0.2 to 0.7. The axis for the flapping oscillations was a streamwise line 0.152 m (6.0 in.) behind the wall used for the image plane; the pitching axis was the midchord line. The mean angle of attack was zero. The experimental and predicted lift and pitching moment at midchord for both the pitching and flapping oscillations and the roll moment at the flapping axis for the flapping oscillation are compared from $k = 0.2$ to $k = 0.8$. The exact definition of the experimental phase for the pitching oscillations could not be determined because of the

ambiguous notation used in Reference 30, but was inferred by comparison between theory and experiment. The loading was measured with an uncertainty of ± 4 percent in magnitude and ± 3 deg in phase angle.

APPENDIX B

COMPUTER PROGRAM USER'S MANUAL

The following material constitutes a user's instruction manual for the Widnall three-dimensional lifting-surface computer program. A complete description is given of the input and output procedures and of all output quantities. In subsequent appendices, listings of program decks and sample input and output are provided.

In order to guide a potential user, it is noted that the lengthy instructions given in this appendix might require several weeks for a person who is already familiar with FORTRAN programming to learn. The appropriate sample calculations should be run before generating any original results.

PROGRAM USAGE

The lifting-surface theory is contained in three computer programs: the steady loading program YKWS, the unsteady program YKWU, and the auxiliary program YKWA. The programs are related to each other as shown in Figure B.1. Both the steady (YKWS) and the unsteady (YKWU) programs calculate load coefficients and also generate, at the option of the user, punched output containing the pressure matrices which characterize the foil configurations being treated. This punched output can then be used to calculate loading for additional sets of downwash conditions in relatively short run time by using the auxiliary program (YKWA).

The three programs are each composed of a main program and several subprograms. All programming has been done in the FORTRAN Extended Language (Version 3.0). The FORTRAN names and mathematical functions of all main programs and subprograms are shown in Tables B.1 through B.3. Listings of the FORTRAN coding for all programs are given in Appendix C.

PROGRAM INPUT DESCRIPTION

Input to the computer programs consists of coding in subprograms in addition to data cards. The subprograms specify the foil geometry and the spanwise pressure modes. The data cards contain foil and flow parameters,

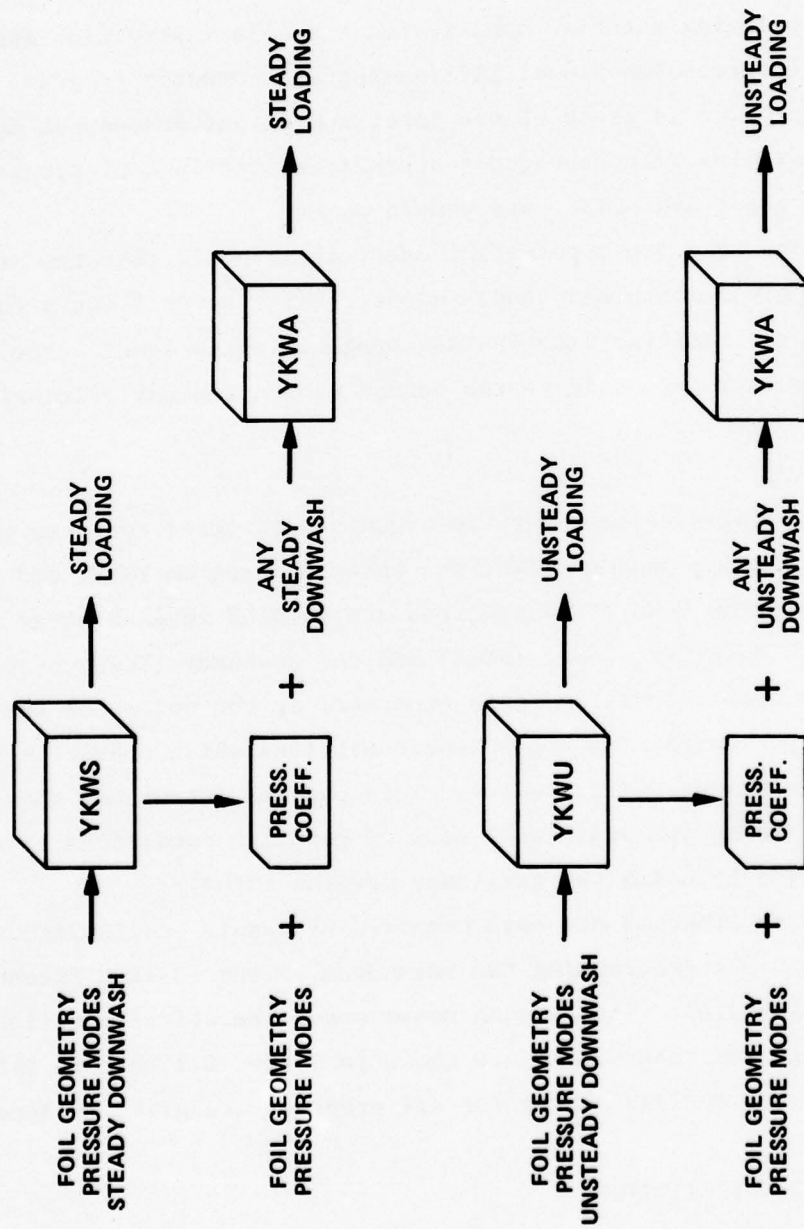


Figure B.1 - Relationship among Programs YKWS, YKWU, and YKWA

TABLE B.1 - COMPOSITION OF DECK FOR PROGRAM 1 (YKWS)

| Program | Function |
|-------------------|---|
| Program YKWS | Main program (steady) |
| Subroutine ANSWER | Calculate steady load coefficients |
| Subroutine CHORD | Calculate chordwise pressure coefficient distribution |
| Subroutine MNGLR | Singular spanwise integration |
| Subroutine KERNEL | Calculate steady kernel function |
| Subroutine MATINS | Matrix inversion |
| Subroutine CHDWS | Chordwise integration (steady) |
| Function GN | Gaussian integration intervals |
| Function WN | Gaussian weighting factors |
| Subroutine STRUCT | Foil geometry |
| Function XLE | Foil geometry |
| Function B | Foil geometry |
| Subroutine FUNCTN | Spanwise pressure modes |

TABLE B.2 - COMPOSITION OF DECK FOR PROGRAM 2 (YKWU)

| Program | Function |
|-------------------|---|
| Program YKWU | Main program (unsteady) |
| Subroutine ANSWU | Calculate unsteady load coefficients |
| Subroutine KERNLU | Calculate unsteady kernel function |
| Subroutine MNGLRU | Singular spanwise integration |
| Subroutine CHDWU | Chordwise integration (unsteady) |
| Function GN | Gaussian integration intervals |
| Function WN | Gaussian weighting factors |
| Subroutine CMPINV | Complex matrix inversion |
| Subroutine MATINV | Matrix inversion |
| Subroutine HINT | Auxiliary in unsteady kernel function calculation |
| Subroutine WINT | Auxiliary in unsteady kernel function calculation |
| Subroutine BIMLI | Auxiliary in unsteady kernel function calculation |
| Function BIML2 | Auxiliary in unsteady kernel function calculation |
| Subroutine BESK | Calculates K Bessel function |
| Subroutine STRUCT | Foil geometry |
| Function XLE | Foil geometry |
| Function B | Foil geometry |
| Subroutine FUNCTN | Spanwise pressure modes |

TABLE B.3 - COMPOSITION OF DECK FOR
PROGRAM 3 (YKWA)

| Program | Function |
|-------------------|--------------------------|
| Program YKWA | Main program (auxiliary) |
| Subroutine FUNCTN | Spanwise pressure modes |
| Function XLE | Foil geometry |
| Function B | Foil geometry |

internal program constants, control point locations, and downwash values on the foil. The method of formulating the required subprograms and data values is described in the following sections.

Representation of Lifting Surface

Subprogram coding is used to supply most of the information about foil geometry required by the lifting-surface calculation. Any combination of foils of arbitrary planform, including both connected and unconnected lifting surfaces, can be treated by the program. However, it should be remembered that, theoretically, all foil surfaces make infinitesimally small angles with the direction of flow.

The foil being specified is located in the (x,y,z) coordinate system of Figure 1. Flow is in the positive x direction. Three user-coded subprograms are used to specify the foil coordinates in terms of two new parameters, the section number and the position along the span of the foil, given as fraction of span. Before coding for these subprograms can be written, however, integration regions on the foil and section numbers must be chosen to be consistent with each other and also with the fraction of span coordinate directions. Each of these quantities will be explained separately. Names of variables given in capital letters refer to computer input quantities which are listed in Table B.4.

Section Number, N. The foil is considered to be composed of N sections of arbitrary extent. For convenience, N should be small and the sections

TABLE B.4 - FORTRAN INPUT NOTATION

| Input | Definition |
|--------|---|
| AF(I) | Spanwise length of Ith section, in units of reference semichord |
| ARM | X-coordinate about which pitching moment is calculated (zero if left blank) |
| B(N,S) | Length of foil semichord at the fractional spanwise position S on foil section N (defined in FUNCTN B(N,S)) |
| EM | Mach number; zero for hydrofoils |
| ETA | Half-width of the singular region (Region I); minimum of 0.1, SOS, and 1.0 - SOS |
| F(I) | Value of the Ith spanwise pressure mode (defined in Subroutine FUNCTN (N,S,F) for fractional spanwise position S on foil section N) |
| IPUNCH | Punched output indicator: IPUNCH = 0 generates no punched output; IPUNCH = 1 generates punched output required for running Program YKWA |
| J3 | Free surface indicator: J3 = 0 signifies infinite depth; J3 = 1 signifies finite depth (a value for the finite foil depth must be given in Subroutine STRUCT) |
| MP | Number of chordwise integration steps in the singular region (may be 6, 8, 10, 16, or 32) |
| N | Section number ($N \leq 6$) |
| NCASE | Number of foil configurations |
| NCMBR | Number of downwash sets for each foil configuration (given once but applies to all configurations); NCMBR = 0 is valid |
| NCP | Number of chordwise integration steps in the nonsingular regions (may be 6, 8, 10, 16, or 32) |
| NI(I) | Number of spanwise integration steps in the Ith region (may be 0, 6, 8, 10, 16, or 32); zero prevents integration over regions which are not needed to represent foil |
| NNNN | Running index used to consecutively number the NCASE foil configurations |
| NOCP | Total number of control points over all sections ($NOCP > NOST$ * NOLT; maximum values are 180 for steady loading and 90 for unsteady loading) |
| NOLT | Number of internally generated chordwise pressure modes ($NOLT \leq 20$) |
| NOST | Number of spanwise pressure modes ($NOST \leq 4$) specified in Subroutine FUNCTN |
| NS | Number of foil sections ($NS \leq 6$) |
| PSI | Arc tangent of the slope dz/dy of the foil surface in the y-z plane when looking upstream (see Figure B.3) |
| RF | Reduced frequency; $b\omega/U$ |
| SF(I) | Ratio of the span of the Ith foil section to the sum of the spans of all foil sections |
| SOS | Spanwise location of control point on a given foil section, specified as fraction of span from the end of the section having $S = 0$ |
| SPAN | Sum of AF values, equal to the total foil span |
| VR(I) | Real part of the downwash at the Ith control point |
| VI(I) | Imaginary part of the downwash at the Ith control point |
| XOC | Chordwise location of control point, specified as fraction of local chord aft of leading edge |
| YS | Fraction of span at which chordwise pressure jump distribution is to be calculated |

should correspond to areas of simple geometry on the foil such as semispans, supporting struts, etc. When geometrical symmetry between two sections of a foil exists, however, input simplification can be achieved by extending the calculation over the similar section without giving it a section number. This procedure involves manipulation of integration regions.

Fraction of Span, S. Each numbered section of the foil must be given a signed coordinate S which specifies the fractional spanwise distance b' from one end of the section to the other. The span S may originate at either end and will range from 0 to 1 in value. The computer calculation assumes that negative values of S correspond to another, unnumbered, section which the program user may wish to have included as part of the complete foil. This unnumbered section would have a geometry describable by the coding used for the numbered section with negative S substituted for positive S.

Integration Regions. The entire foil configuration is divided into four or more regions for spanwise integration of the kernel function. The regions change in location for each control point, and, therefore, can be visualized for only one control point at a time. A narrow chordwise strip centered at the control point is called Region I. η is the spanwise half-width of Region I. The remainder of the foil section outboard (larger S) of Region I is Region II, while the inboard part is Region IV. Region III encompasses the unnumbered, negative-S counterpart (of the numbered wing section composed of Regions I, II, and IV). Other even-numbered regions consist of the remaining foil sections, while odd-numbered regions are the negative-S counterparts of the remaining sections. A typical set of integration regions is shown on the foil in Figure B.2.

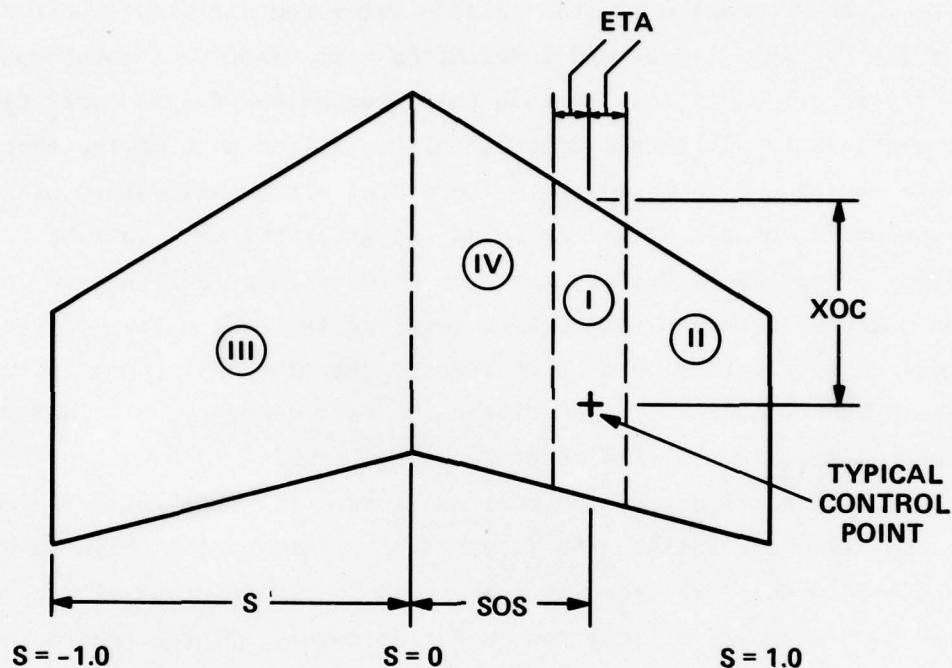
Integration regions are designed to permit special integration techniques to be used in the vicinity of each control point, where a singularity occurs in the kernel function. Because of the way in which the integration regions are chosen, the data inputs $NI(J)$, which designate the number of spanwise integration stations in the Jth region, are also used to

indicate whether a region exists. A zero value for all $NI(J)$ where J is odd and greater than 1 prevents integration over negative- S counterparts of specified foil sections. Because the integration regions cover different sections for different control points, all or none of the sections must have negative- S counterparts. Therefore, either all values of $NI(J)$ must be nonzero, or all $NI(J)$ for J odd and greater than 1 must be zero.

After a foil configuration has been divided into sections and integration regions have been selected to comprise the full extent of the foil, the required subprograms must be written to describe foil geometry and spanwise pressure modes. In describing the foil geometry, all foil dimensions are given in units of a reference length, which is usually taken as the root semichord of one of the foil sections. It, therefore, is convenient to place the foil in the (x,y,z) coordinate system shown in Figure 1 with the reference semichord on the x -axis in the interval $-1 \leq x \leq 0$, although such a choice of location is not necessary. Three subprograms describe the location and planform of the foil in this frame of reference. The subprograms and their variables are as follows.

Subroutine STRUCT. Subroutine STRUCT (N,S,Z,Y,PSI) defines the y and z coordinates and the slope at each point on the foil. The parameter PSI is defined to be the arc tangent of the slope dz/dy of the foil surface in the y - z plane when looking upstream as shown in Figure B.3; N denotes the foil section; Y and Z represent the y and z coordinates of the foil. The fractional distance along the span of the section, S , denoted as b' in Equation (2), can be chosen to originate at either end of the section. The fractional distance S will be set equal to $-S$ when unnumbered counterparts to section N are being described. If more than one foil configuration is treated with a single computer run, the variable $NNNN$, placed in labeled common blocks $CNRA$, provides a running index to number the various configurations.

Foils may be treated either with or without a free surface. The $J3$ input described below indicates whether or not a free surface is to be included. The free surface is represented by an image foil which is



NOTE: INTEGRATION REGIONS DENOTED
BY ROMAN NUMERALS

Figure B.2 - Integration Regions for a Typical Control Point

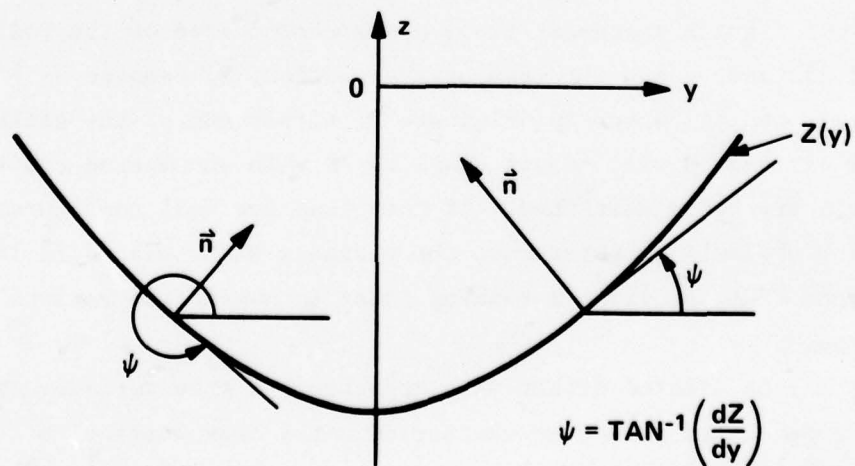


Figure B.3 - View of Nonplanar Foil Looking Upstream

generated by using the given foil geometry with z -values of opposite sign. Therefore, foils beneath a free surface must be given z -coordinates so that the plane $z = 0$ represents the free surface. Otherwise the foil may be placed anywhere along the z -axis.

Function XLE. Function $XLE(N,S)$ defines the x -coordinate of the leading edge of the foil. Functions N and S are the section number and fractional spanwise coordinate b' , respectively. The variable $NNNN$, placed in labeled common block $CNRA$, provides a running index corresponding to succeeding configurations treated with a single computer run.

Function B. Function $B(N,S)$ defines the length of the semichord of the foil at the fractional spanwise position S . Function N is the number of the foil section. The variable $NNNN$, placed in labeled common block $CNRA$, provides a running index as previously described.

Spanwise Pressure Modes

End Conditions. As described above, the Widnall program predicts load distributions on the foil by summing several terms of a series which is used to represent the pressure jump between the upper and lower surface of the foil. Each term of the series consists of a product of a chordwise and a spanwise pressure mode. The chordwise modes are taken from two-dimensional wing theory and are built into the program. The program user must specify the spanwise pressure modes.

This set of spanwise pressure modes must be chosen to conform to physical flow conditions. In particular, each set of modes must satisfy the following boundary conditions at the ends of foil sections.

- a. Foil loading drops to zero at the end of a cantilevered foil and at the free surface on a surface-piercing foil.
- b. Foil loading is nonzero at an intersection of two or more lifting surfaces, and at an intersection of a lifting surface and a reflecting plane.
- c. Pressure jumps along a closed path around an intersection of two or more foil sections must sum to zero.

Note that the above conditions place restrictions on the magnitude of each pressure mode at the ends of foils. When zero loading is required at the end of a foil, each of the spanwise pressure modes must become zero. However, when nonzero loading contributions are required, at least one of the modes must be nonzero. Each mode must be specified on all foil sections, although the shape of the mode does not have to be the same on all the sections, and each mode must satisfy condition (c) independently of the other modes.

Certain foil configurations suggest boundary conditions on the spanwise slopes of the modes, in addition to the above conditions on the magnitudes of the modes, at the ends of the foils:

- d. Loading on submerged foil tips is approximately elliptical.
- e. Loading near the free surface on surface-piercing foils approached zero less steeply than does an elliptical distribution.
- f. The load distribution slope at foil intersections is approximately zero (an end-plate effect).

It is convenient to satisfy all of the above boundary conditions which apply to a given foil by specifying one pressure mode having all requisite end-point magnitudes and slopes. Additional modes are then formed from the first mode multiplied by integral powers of S and/or $(1.0-S)$. The additional modes permit refinement of the pressure distribution by the calculation process.

The pressure modes must satisfy one final condition:

- g. Both antisymmetric and symmetric pressure modes must be included on foil surfaces which do not have purely symmetric loading.
- Inclusion of both symmetric and antisymmetric modes allows the program complete flexibility in proportioning the loading among different surfaces. A commonly-encountered foil configuration requiring the use of both types of modes is the inverted-T foil at a nonzero roll angle beneath a free surface, an example of which is treated below.

Subroutine FUNCTN. The subprogram Subroutine FUNCTN (N,S,F) is used to define the pressure modes for use in the program. Function F is an array which contains the ordinates of the pressure modes as functions of section number N and fractional spanwise position S.

The direction of a pressure jump which is represented by a given mode is designated by a sign convention based on the definition of the local foil slope PSI. The positive lift direction is given by a vector \vec{n} normal to the foil and having a positive z-component, as shown in Figure B.3. This convention allows interpretation of the sign of the lift distribution output.

Data Card Input

Input Format. Data cards are to be punched with the input quantities shown in Table B.5 for each of the three programs. The quantities were defined in Table B.4. The required formats are shown to the right of the input quantities, and the number of the column farthest to the right in the field in which the input quantity is to be placed is shown above the quantity.

Downwash Input. The downwash is the velocity which must be added to the free stream velocity to produce the flow at the surface of the foil. The downwash on a given foil surface is normal to the foil surface and to the free stream (in accordance with the assumption of small angles of attack) and has a direction opposite to the direction of positive lift (\vec{n}). Downwash magnitude is determined by the boundary condition that fluid cannot penetrate the surface of the foil. In the case of steady loading, the boundary condition requires tangential flow along the surface, so that the downwash to be input to the program is v_n/U , where

$$\frac{v_n}{U} = \sin \alpha \approx \alpha \text{ (Steady Downwash)} \quad (B.1)$$

TABLE B.5 - DATA CARD INPUT

TABLE B.5a - PROGRAM 1 CARD INPUT

Program 1 (YKWS) Steady Loading

| | | | |
|---------------|-------------------------------|--|--------------------------|
| NCASE Sets | 5 10 15 | Card 1: NCASE/NCMBR/IPUNCH/ | FORMAT(3I5) |
| | | Card 2: Title (any 80 characters) | FORMAT(1H1,80H) |
| | 10 20 25 30 35 40 45 50 55 65 | Card 3: RF/EM/NS/NOCP/NOLT/NOST/NCP/MP/J3/ARM/ | FORMAT(2F10.5,7I5,F10.5) |
| | 5 10 | Card 4: NI(2)/NI(3)/...NI(2*NS+2)/ | FORMAT(20I5) |
| | 10 20 | Card 5: AF(1)/AF(2)/...AF(NS)/ | FORMAT (10F10.5) |
| NCMBR Sets | 5 15 25 35 | NOCP Control Point Cards: N/XOC/SOS/ETA | FORMAT(15,3F10.5) |
| | | Next Card: Downwash Title (any 80 characters) | FORMAT(1H1,80H) |
| | 12 36 60 | (NOCP/3) Downwash Cards: VR(1)/VR(2)/VR(3)/ ...VR(NOCP)/ | FORMAT(3(F12.3,12X)) |
| | 10 | Next Card(s): YS/(one YS card for each section--NS total) | FORMAT(F10.5) |
| | | (begin at Card 2 again for next case) | |

TABLE B.5 (Continued)

TABLE B.5b - PROGRAM 2 CARD INPUT

Program 2 (YKWU) Unsteady Loading

| | | | |
|---------------|-------------------------------|---|--------------------------|
| NCASE Sets | 5 10 15 | Card 1: NCASE/NCMBR/IPUNCH/ | FORMAT(3I5) |
| | | Card 2: Title (any 80 characters) | FORMAT(1H1,80H) |
| | 10 20 25 30 35 40 45 50 55 65 | Card 3: RF/EM/NS/NOCP/NOLT/NOST/NCP/MP/J3/ARM/ | FORMAT(2F10.5,7I5,F10.5) |
| | 5 10 | Card 4: NI(2)/NI(3)/...NI(2*NS+2)/ | FORMAT(20I5) |
| | 10 20 | Card 5: AF(1)/AF(2)/...AF(NS)/ | FORMAT(10F10.5) |
| NCMBR Sets | 5 15 25 35 | NOCP Control Point Cards: N/XOC/SOS/ETA | FORMAT(15,3F10.5) |
| | | Next Card: Downwash Title (any 80 characters) | FORMAT(1H1,80H) |
| | 12 24 36 | (NOCP/3) Downwash Cards: VR(1)/VI(1)VR(2)/ 48 60 72 VI(2)/VR(3)/VI(3)/...VR(NOCP)/VI(NOCP)/ | FORMAT(6F12.3) |
| | | (begin at Card 2 again for next case) | |

TABLE B.5 (Continued)

TABLE B.5c - PROGRAM
3 CARD INPUT

Program 3 (YKWA) Auxiliary Program

| | | |
|--------------------------------------|--|---------------------------------------|
| Output from YKWS or YKWU | Card 1: Title (any 80 characters) | FORMAT(80H) |
| | Card 2: Free Surface Card | FORMAT(80H) |
| | Card 3: RF/SPAN/NS/NOLT/NOST/NOCP/MP/NCP/EM/ 10 20 25 30 35 40 45 50 60 65 70 NCMBR/ARM/ | FORMAT(2F10.5,615, F10.5,15,F10.5) |
| | Card 4: AF(1)/AF(2)/...AF(NS)/ 5 10 | FORMAT(6F10.5) |
| | Card 5: NI(2)/NI(3)/...NI(2*NS+2)/ [PR] matrix [PI] matrix (if unsteady) | FORMAT(14I5) |
| NCMBR Sets | Next Card: Downwash Title (any 80 characters) | FORMAT(1H1,80H) |
| | (NOCP/3) Downwash Cards: VR(1)/VI(1)/VR(2)/ 12 24 36 48 60 72 VI(2)/VR(3)/VI(3)/...VR(NOCP)/VI(NOCP)/ | FORMAT(6F12.3) |
| | if steady: | |
| | Next Card(s): YS/(one YS card for each 10 section--NS total) | FORMAT(F10.5) |

and α is the local angle of attack. Note that downwash velocity is given in units of the free stream velocity. As indicated in this expression, the downwash input to the program is the local angle of attack (in radians), in keeping with the theoretical assumption that foil angles relative to the flow are small. Camber is thus represented by variations in $v_n/U = \alpha$ as a function of x .

Steady downwash is input to program YKWS or YKWA using the VR array. For example, a downwash input of

$$VR(I) = 0.1, I = 1, NOCP \quad (B.2)$$

would indicate an uncambered foil at an incidence of 0.1 radian.

Unsteady loading results from either foil oscillation or from unsteady flow past the foil such as that due to the orbital velocities of waves. In the first case (foil oscillation), since the particles follow the motion of the foil, the downwash velocity is the velocity of the foil perpendicular to the mean position of the foil, which is assumed to be at zero angle of attack. Downwash input is the sinusoidal amplitude of the downwash velocity, in units of the free stream speed. If the position of the foil surface is given as

$$f(x,y,z,t) = 0 \quad (\text{B.3})$$

then the normal velocity of the surface is

$$\frac{Df}{Dt} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial x} \frac{\partial x}{\partial t} + \frac{\partial f}{\partial y} \frac{\partial y}{\partial t} + \frac{\partial f}{\partial z} \frac{\partial z}{\partial t} \quad (\text{B.4})$$

In this expression, $\partial y/\partial t = \partial z/\partial t = 0$ because flow is restricted to the x-direction, while $\partial x/\partial t = U$, the flow speed. Since foil motion is positive upward and downwash v_n is positive downward,

$$v_n = - \frac{Df}{Dt} = - \frac{\partial f}{\partial t} - U \frac{\partial f}{\partial x} \quad (\text{B.5})$$

The downwash may be expressed in terms of the amplitude of displacement of the foil from its mean position, which is a sinusoidally varying function

$$\delta(x,y,z,t) = \delta_0(x,y,z)e^{i\omega t} \quad (\text{B.6})$$

where

$$f = \bar{f}(x,y,z) + \delta(x,y,z,t) \quad (\text{B.7})$$

Using δ , the downwash becomes

$$v_n = - \left[i\omega\delta_o + U \frac{\partial\delta_o}{\partial x} \right] e^{i\omega t} \quad (B.8)$$

If the reduced frequency k is introduced, the downwash may be expressed as follows:

$$k = c\omega/2U \quad (B.9)$$

$$v_n = - \left[\frac{i2kU\delta_o}{c} + U \frac{\partial\delta_o}{\partial x} \right] e^{i\omega t} \quad (B.10)$$

which is then normalized in terms of U to give

$$\frac{v_n}{U} = - \left[i2k \frac{\delta_o}{c} + \frac{\partial\delta_o}{\partial x} \right] e^{i\omega t} \quad \left| \begin{array}{l} \text{Unsteady Downwash} \\ \text{(Foil Oscillation)} \end{array} \right| \quad (B.11)$$

The real component, $-\partial\delta_o/\partial x$, is the rate of change of the unsteady displacement amplitude in the streamwise direction, and is, therefore, nonzero for pitching motion and zero for bending motion.

The second cause of unsteady downwash is time-varying flow past the foil. An analysis is presented for the time-varying flow experienced by a foil traveling beneath waves due to a head sea in deep water. Surface waves cause the water particles beneath the surface to move in circular paths with an orbital velocity U' . The magnitude of the orbital velocity at a given depth h is given by³³

$$U' = \omega' \frac{\zeta_w}{2} \exp(2\pi h/\lambda) \quad (B.12)$$

Both vertical and horizontal components of the orbital velocity contribute to the unsteady downwash, but at a relative phase difference of 90 deg. The unsteady downwash due to the orbital velocity's vertical component is

$$U'e^{i(\omega't+\pi/2)} \quad (B.13)$$

The unsteady downwash due to the orbital velocity's horizontal component is

$$U'\alpha_o e^{i\omega't} \quad (B.14)$$

where α_o is the local slope of the foil, whether due to camber, angle of attack, or both. The total downwash due to wave motion is then

$$v_n = \left[U'\alpha_o + iU' \right] e^{i\omega't} \quad (B.15)$$

In this expression, U' and α_o are to be evaluated according to the wave characteristics and the location on the foil of each control point. The resultant downwash is similar in form to the downwash for pure pitching oscillation when α_o is nonzero and is similar to the downwash for pure heaving motion when α_o is zero.

The computer program requires, as input, values for the unsteady downwash seen by the foil traveling through the waves at speed U . The above expression gives the amplitude of the downwash seen by the foil, but ω' must be replaced by ω , the wave encounter frequency. The resulting downwash experienced by the foil is

$$\frac{v_n}{U} = \left[\frac{U'}{U} \alpha_o + i \frac{U'}{U} \right] e^{i\omega t} \left| \begin{array}{l} \text{Unsteady Downwash} \\ \text{(Wave Motion)} \end{array} \right| \quad (B.16)$$

The downwash is input to the computer program in the form

$$\left. \begin{array}{l} \text{VR(I)} = \text{real component} \\ \text{VI(I)} = \text{imaginary component} \end{array} \right\} \text{I} = 1, \text{ NOCP}$$

where the unsteady exponential $e^{i\omega t}$ is assumed by the program and is not a direct input. The wave encounter frequency ω is input as part of the reduced frequency RF.

Input Restrictions. Limitations on input parameter values, based on program structure or dimensioning, are indicated in Table B.4. Suggested input values are listed in Tables 2 and 6.

PROGRAM OUTPUT DESCRIPTION

All three programs generate printed output giving the loading on the subject foil systems and the input that was used to generate that loading. The output may be summarized as follows.

First, all input data except the downwash values are printed out. Second, Programs 1 and 2 print all matrices involved in the matrix inversion, including the resulting unit matrix. The size of the off-diagonal elements of the unit matrix indicates the quality of the inversion. Third, the resulting pressure matrix ($[\text{PR}] + i[\text{PI}]$) is printed. This matrix is contained in the input for Program 3. Finally, downwash values, pressure mode coefficients, load coefficients, and center of pressure locations are printed by all programs. A chordwise pressure jump distribution is also given by Programs 1 and 3.

The pressure mode coefficients appear in the printed output as the CR and CI arrays. Array CR contains the steady loading coefficients or the real part of the unsteady coefficient, while CI contains the imaginary part of the unsteady coefficients. The matrix elements correspond to the coefficients a_{nm} found in Equation (2) in the following manner:

$$\left. \begin{aligned} \operatorname{Re}(a_{nm}) &= CR(n+1, m+1) \\ \operatorname{Im}(a_{nm}) &= CI(n+1, m+1) \end{aligned} \right\} \begin{aligned} n &= 0, 1, 2, \dots, NOLT \\ m &= 0, 1, 2, \dots, NOST \end{aligned}$$

Load coefficients* are presented as both spanwise distributions and total loading on each foil section. The spanwise distributions consist of lift, pitching, and roll moment coefficients per unit span which are given at intervals of 5 percent of section span on each foil section. These spanwise coefficients are defined in Table B.6. The spanwise pressure modes (F) selected by the program user are also listed at 5 percent intervals for reference. Total lift and moment coefficients are obtained by numerical integration of the spanwise distributions. Unsteady load coefficients are given in terms of both magnitude and phase angle. An example of printed output from each program is given along with the sample calculations.

Punched output can be obtained from Programs 1 and 2 and is required for running Program 3. When a value of 1 is input for IPUNCH, all necessary parameters for running Program 3 except the downwash cases are punched by having them written on the punch tape.

A center of pressure is calculated for each section whether the loading is steady or unsteady. For steady loading, the conventional center of pressure, at which the lift appears to act, is calculated and is given in terms of its x-coordinate and the fraction of the section span from the end of the section at which $S = 0$. For unsteady loading, the center of pressure is calculated in the following manner. Let the lift and pitching moment be given by

$$L = L_0 \cos \omega t \quad (B.17)$$

$$M = M_0 \cos (\omega t - \phi) \quad (B.18)$$

*Load coefficients are only valid on sections having constant slope (PSI = constant); this restriction does not apply to pressure jump distribution coefficients CR and CI.

TABLE B.6 - OUTPUT LOAD COEFFICIENTS

| | |
|------------|---|
| CLR, CLI | Real and imaginary components of spanwise lift coefficient; (lift on a unit span)/ $q c_o$; positive lift opposite to positive downwash |
| CLMG | Magnitude of spanwise lift coefficient; $(CLR)^2 + (CLI)^2$ |
| CLPH | Phase angle by which lift leads displacement; $\tan^{-1} (CLI/CLR)$, deg |
| CPMR, CPMI | Real and imaginary components of spanwise pitching moment coefficient calculated about $x = ARM$, positive tending to twist foil nose in direction of positive lift; (pitching moment on a unit span)/ $q c_o^2$ |
| CPMG | Magnitude of spanwise pitching moment coefficient; $(CPMR)^2 + (CPMI)^2$ |
| CPPH | Phase angle by which pitching moment leads displacement; $\tan^{-1} (CPMI/CPMR)$, deg |
| CRMR, CRMI | Real and imaginary components of spanwise roll moment coefficient, calculated about section root chord (where $S = 0$); positive tending to roll foil in direction of positive lift; (roll moment due to a unit span)/ $q c_o^2$ |
| CRMG | Magnitude of spanwise roll moment coefficient; $(CRMR)^2 + (CRMI)^2$ |
| CRPH | Phase angle by which roll moment leads displacement; $\tan^{-1} (CRMI/CRMR)$, deg |
| CP | Pressure jump coefficient (equivalent to lift per unit area in units of dynamic pressure); $2\Delta p/\rho U^2$ |

where the moment is calculated about an axis at $x = a$. By expanding the moment expression, it is possible to express the moment in terms of components which are in-phase and 90 deg out-of-phase with the lift.

$$M = M_o \cos \phi \cos \omega t + M_o \sin \phi \sin \omega t \quad (B.19)$$

The distance between the specified moment axis at $x = a$ and the unsteady center of pressure, $x = b$, is given by the moment component in phase with the lift divided by the lift, or

$$b - a = (M_o \cos \phi) / L_o \quad (B.20)$$

The following considerations may help the reader to understand the nature of the unsteady center of pressure. If the unsteady pitching moment were calculated about an axis passing through $x = b$, its magnitude would be a minimum. In addition, it would have no component in-phase with the lift and would, therefore, be 90 deg out-of-phase with the lift. Measurement of either of these characteristics would permit a direct experimental determination of the unsteady center of pressure.

The program output gives the location of the unsteady center of pressure in terms of its x-coordinate, b , and the fraction of the section span from the root of the section.

OPERATING INSTRUCTIONS

The Widnall lifting-surface program has been adapted to run on the Control Data Corporation 6700 digital computer at DTNSRDC. All programs and subprograms are written in the FORTRAN Extended language (Version 3.0).

In its present form, the program requires about 205,000 (octal) memory locations. This amount of memory permits selection of the full range of numerical parameter values shown in Table B.5. The standard input used in the present study could be run with substantially less memory if the user reduced the appropriate array dimensions in the program. Conversely, larger arrays and increased dimensions would be required if the user desired more control points and larger numbers of integration intervals than are given in Table B.4.

Program run time varies according to the value of numerical input parameters. With the standard input, an execution time of about 35 sec was obtained, expressed in terms of the DTNSRDC convention of time required on a CDC-6400 computer. Unexpectedly and for unknown reasons, runs made

at AR = 1 required about twice as much time for execution (about 80 sec) as runs at AR = 6 and 10. Compilation of the source deck took 18 sec. It is concluded that the computer costs for using the program will normally be small compared to the cost of learning how to use the program and preparing input data.

SAMPLE CALCULATIONS

Sample calculations are presented to illustrate the use of each of the three programs. All data and subprogram codings corresponding to the sample calculations are included in the program listings given in Appendix C. Discussion of each case consists of description of the input data and presentation of printed output obtained from a computer run.

Program 1 (YKWS)

The foil configuration chosen as an example for the steady loading test case permits several aspects of program use to be illustrated. However, the calculated loading cannot be considered accurate because the numerical calculation has probably not achieved a stable condition. Considering that 60 control points were recommended on a single foil section, the sample calculation's use of only 16 on each section of a total of 48 on all three sections is probably inadequate for numerical stability. The stability of multisection foil calculations has, in fact, not been studied. Therefore, this sample calculation must be regarded as a test case only, for acquainting the user with program capabilities and providing a means of verifying other copies of the program at relatively low cost.

The subject foil is an inverted-T configuration which corresponds to a hydrofoil model for which loading has been determined experimentally.³⁴ The foil system, shown in Figure B.4, is rolled relative to the vertical and is surface-piercing. As a result, nonsymmetrical loading will occur on the foils even though the strut has zero angle of attack.

Three sections are used to represent the three foil surfaces. Values of NI(3), NI(5), and NI(7) have been set equal to zero to prevent integration over negative values of S for all sections.

Foil geometry is specified in the user-coded subprograms. Subroutine STRUCT gives the y- and z-coordinates for each section. Leading-edge

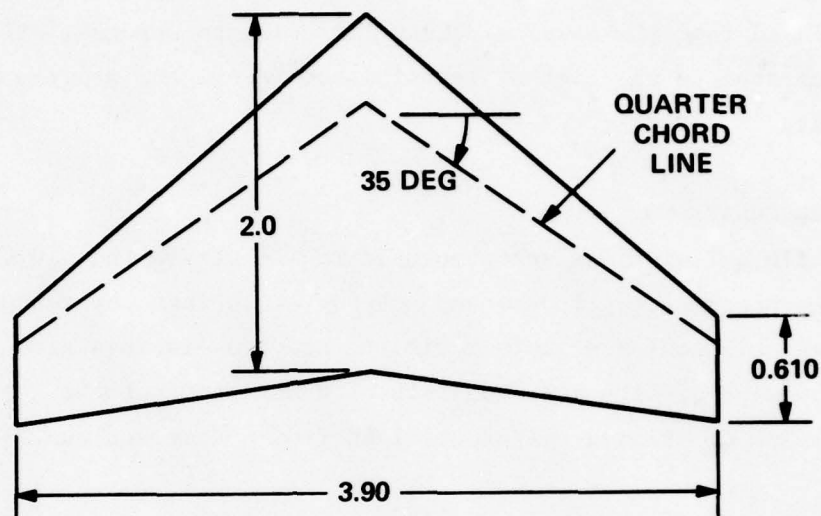


Figure B.4a - Foil Planform

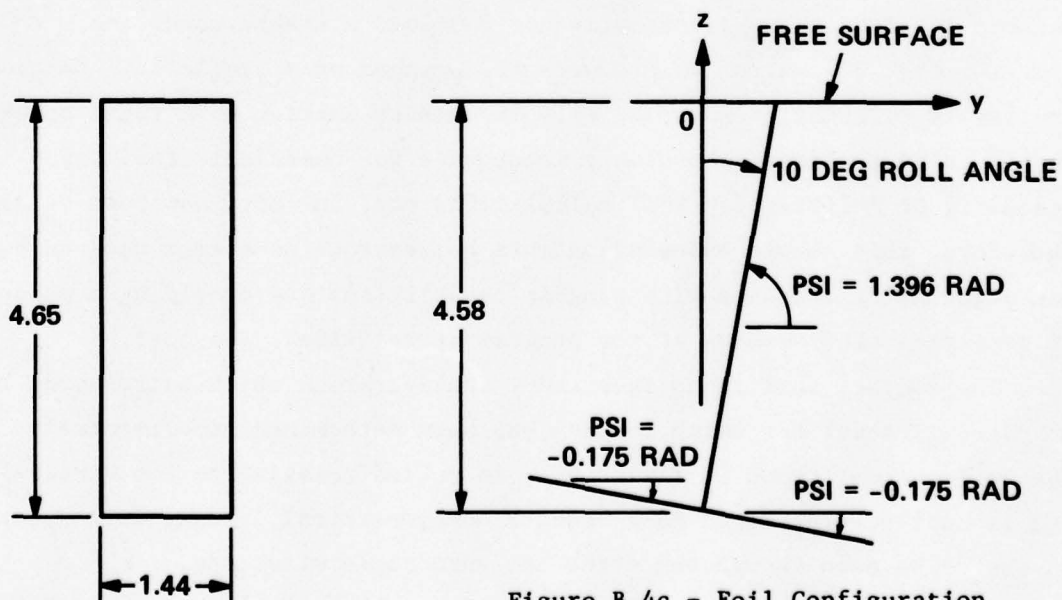


Figure B.4b - Strut Planform

Figure B.4c - Foil Configuration Looking Upstream

Figure B.4 - Foil Configuration for Steady Loading Test Case

x-coordinates are given in Function XLE. Local chord lengths for the tapered foils and the untapered strut appear in Function B.

Spanwise pressure modes are specified in Subroutine FUNCTN. Elliptical loading has been specified at the tips of the foils, and parabolic loading specified at the surface-piercing end of the strut. Both symmetric and antisymmetric modes are required on the foils in order to permit unequal loading. Only the minimum number of pressure modes has been specified; additional modes would allow refinement of the spanwise loading distribution shapes.

Control points were placed in networks of 4 spanwise by 4 chordwise on each section, making a total of 48 control points. Downwash values were based on the NACA 16-407, $a = 1.0$ foil profiles, with the uncambered strut placed at zero incidence.

Printed output from the computer run is shown in Appendix D.

Program 2 (YKWU)

A relatively simple rectangular foil configuration¹⁵ is used to illustrate an unsteady-loading calculation. The fully-wetted foil, shown in Figure B.5, undergoes forced deflection in an approximate first torsion mode.

A single section represents one half-span of the foil, while S-symmetry is invoked to represent the other half-span produced by a root reflection plate. The symmetrical half-span is included in the integration by making NI(3) nonzero. Foil geometry is specified in the subprograms listed in Appendix C. Four elliptical spanwise pressure modes were selected. Input data includes the reduced frequency value of 1.97, locations of 16 control points, and unsteady downwash values corresponding to the experimentally determined torsional mode shape at reduced frequency 1.97. Again, the use of 16 control points rather than the 60 recommended for stability is intended only to acquaint the user with the program.

Printed output is shown in Appendix E. In addition to the printed output, the PR and PI matrices, along with several auxiliary quantities, were placed on punch cards for use in Program 3. The sample calculation for Program 3 uses this punched output.

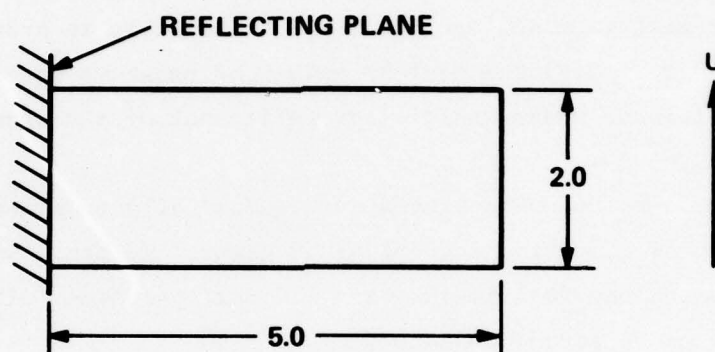


Figure B.5a - Foil Planform

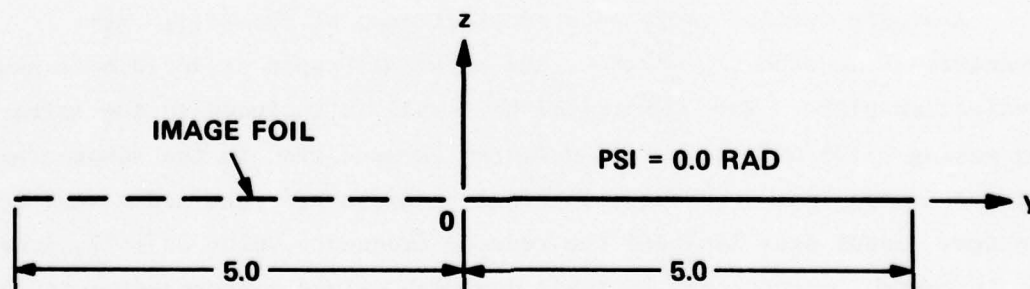


Figure B.5b - Foil Configuration
Looking Upstream

Figure B.5 - Foil Configuration for Unsteady Loading Test Case

Program 3 (YKWA)

The unsteady load calculation described above is continued as the sample calculation for Program 3. The foil geometry and pressure mode subprograms are used in the same form as in Program 2. Data cards include the punched output from Program 2 and the same unsteady downwash values used for Program 2.

Printed output is shown in Appendix F.

APPENDIX C
PROGRAM LISTINGS AND INPUT FOR SAMPLE CALCULATIONS

Program 1 Listing (continued)


```

      SUBROUTINE STRUCT(N,S,Z,Y,PSI)
C   HYSTAD INVERTED T-FOIL STEADY LOADING TEST CASE
C   H=DEPTH TO FOIL MIDSPAN      TH=ROLL ANGLE IN RADIANS
C   NOTE THAT H DEFINED POSITIVE AS DEPTH/MN CHD
      COMMON /CNRA/ NNNN
      H=3.52
      TH=0.17453
      H=H*1.301
      IF(N-2)1,2,3
1    PSI=-TH
      Y=1.9495*S*COS(TH)-H*TAN(TH)
      Z=-1.9495*S*SIN(TH)-H
      RETURN
2    PSI=-TH
      Y=-1.9495*S*COS(TH)-H*TAN(TH)
      Z=1.9495*S*SIN(TH)-H
      RETURN
3    PSI=(3.14159/2.0)-TH
      Y=-H*TAN(TH)*(1.0-S)
      Z=-H*(1.0-S)
      RETURN
      END
      FUNCTION XLE(N,S)
C   HYSTAD INVERTED T-FOIL STEADY LOADING TEST CASE
      COMMON /CNRA/ NNNN
      IF(N-2)1,1,3
1    XLE=-1.0+(1.9495*0.7002+0.350)*ABS(S)
      RETURN
3    XLE=-0.493
      RETURN
      END
      FUNCTION R(N,S)
C   HYSTAD INVERTED T-FOIL STEADY LOADING TEST CASE
      COMMON /CNRA/ NNNN
      IF(N-2)1,1,3
1    R=1.0-0.695*S
      RETURN
3    R=1.442
      RETURN
      END

```

Program 1 User-Coded Subprograms


```

      SUBROUTINE FUNCTN(N,S,F)
C  HYSTAD INVERTED T-FOIL STEADY LOADING TEST CASE
      COMMON /CNRA/NNNN
      DIMENSION F(6)
      DO 519 J=1,6
519  F(J)=0.0
      E=1.0-S**2
      IF (N-2) 1,2,3
1  F(1)=SQRT(F)*(-0.05)
   F(2)=SQRT(E)*(+0.05)
   RETURN
2  F(1)=SQRT(F)*(+0.04 )
   F(2)=SQRT(F)*(+0.05)
   RETURN
3  F(1)=F*0.09
   RETURN
      END

```

Program 1 User-Coded Subprograms (continued)

| C | 1 | 1 | 1 | HYSTAD | INVERTED | T-FOIL | STEADY | LOADING | TEST | CASE--PROGRAM | CHECK ONLY |
|--------|-------|--------|-------|--------|----------|--------|--------|---------|------|---------------|------------|
| 0.0 | 0.0 | 0.0 | 3 | 48 | 3 | 2 | 10 | 10 | 1 | | |
| 10 | 0 | 10 | 0 | 10 | 0 | 10 | | | | | |
| 1.9495 | | 1.9495 | | 4.651 | | | | | | | |
| 1 | .1170 | .9397 | .0603 | | | 10 | 10 | | | | |
| 1 | .1170 | .7660 | .1 | | | 10 | 10 | | | | |
| 1 | .1170 | .5000 | .1 | | | 10 | 10 | | | | |
| 1 | .1170 | .1730 | .1 | | | 10 | 10 | | | | |
| 1 | .4132 | .9397 | .0603 | | | 10 | 10 | | | | |
| 1 | .4132 | .7660 | .1 | | | 10 | 10 | | | | |
| 1 | .4132 | .5000 | .1 | | | 10 | 10 | | | | |
| 1 | .4132 | .1730 | .1 | | | 10 | 10 | | | | |
| 1 | .75 | .9397 | .0603 | | | 10 | 10 | | | | |
| 1 | .75 | .7660 | .1 | | | 10 | 10 | | | | |
| 1 | .75 | .500 | .1 | | | 10 | 10 | | | | |
| 1 | .75 | .1730 | .1 | | | 10 | 10 | | | | |
| 1 | .9698 | .9397 | .0603 | | | 10 | 10 | | | | |
| 1 | .9698 | .7660 | .1 | | | 10 | 10 | | | | |
| 1 | .9698 | .5 | .1 | | | 10 | 10 | | | | |
| 1 | .9698 | .1730 | .1 | | | 10 | 10 | | | | |
| 2 | .1170 | .9397 | .0603 | | | 10 | 10 | | | | |
| 2 | .1170 | .7660 | .1 | | | 10 | 10 | | | | |
| 2 | .1170 | .5000 | .1 | | | 10 | 10 | | | | |
| 2 | .1170 | .1730 | .1 | | | 10 | 10 | | | | |
| 2 | .4132 | .9397 | .0603 | | | 10 | 10 | | | | |
| 2 | .4132 | .7660 | .1 | | | 10 | 10 | | | | |
| 2 | .4132 | .5000 | .1 | | | 10 | 10 | | | | |
| 2 | .4132 | .1730 | .1 | | | 10 | 10 | | | | |
| 2 | .75 | .9397 | .0603 | | | 10 | 10 | | | | |
| 2 | .75 | .7660 | .1 | | | 10 | 10 | | | | |
| 2 | .75 | .500 | .1 | | | 10 | 10 | | | | |
| 2 | .75 | .1730 | .1 | | | 10 | 10 | | | | |
| 2 | .9698 | .9397 | .0603 | | | 10 | 10 | | | | |
| 2 | .9698 | .7660 | .1 | | | 10 | 10 | | | | |
| 2 | .9698 | .5 | .1 | | | 10 | 10 | | | | |
| 2 | .9698 | .1730 | .1 | | | 10 | 10 | | | | |
| 3 | .1170 | .9397 | .0603 | | | 10 | 10 | | | | |
| 3 | .1170 | .7660 | .1 | | | 10 | 10 | | | | |
| 3 | .1170 | .5000 | .1 | | | 10 | 10 | | | | |
| 3 | .1170 | .1730 | .1 | | | 10 | 10 | | | | |
| 3 | .4132 | .9397 | .0603 | | | 10 | 10 | | | | |
| 3 | .4132 | .7660 | .1 | | | 10 | 10 | | | | |
| 3 | .4132 | .5000 | .1 | | | 10 | 10 | | | | |
| 3 | .4132 | .1730 | .1 | | | 10 | 10 | | | | |

Program 1 Punch Card Input

| | | | | |
|---------|-------|-------|----|----|
| 3 .75 | .9397 | .0603 | 10 | 10 |
| 3 .75 | .7660 | .1 | 10 | 10 |
| 3 .75 | .500 | .1 | 10 | 10 |
| 3 .75 | .1730 | .1 | 10 | 10 |
| 3 .9698 | .9397 | .0603 | 10 | 10 |
| 3 .9698 | .7660 | .1 | 10 | 10 |
| 3 .9698 | .5 | .1 | 10 | 10 |
| 3 .9698 | .1730 | .1 | 10 | 10 |

C HYSTAD FOIL AT 4 DEG. INCIDENCE

| | | |
|-------|-------|-------|
| 0.022 | 0.022 | 0.022 |
| 0.022 | 0.062 | 0.062 |
| 0.062 | 0.062 | 0.096 |
| 0.096 | 0.096 | 0.096 |
| 0.153 | 0.153 | 0.153 |
| 0.153 | 0.022 | 0.022 |
| 0.022 | 0.022 | 0.062 |
| 0.062 | 0.062 | 0.062 |
| 0.096 | 0.096 | 0.096 |
| 0.096 | 0.153 | 0.153 |
| 0.153 | 0.153 | 0.000 |
| 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 |
| 0.000 | 0.000 | 0.000 |
| 0.0 | | |
| 0.0 | | |
| 0.0 | | |

Program 1 Punch Card Input (continued)

Program 2 Listing (continued)


```
AL(1)=1.7AN(T(METAIL)/2.)
IF(NOL1.EQ.1) GO TO 38
DO 37 J=2,NOL1
  AL(J)=1.72*(2*(J-1))**SIN(FLOAT(J-1)*M(TETAIL))
37 CONTINUE
38 C=MIN(1,MCP1)*SIN(T(METAIL))*WGHT
DO 39 K=1,NOL1
  PRICKAL(K)=C*(T(K)-AL(K))
  C=PRICKAL(K)*C*(T(K)-AL(K))
39 CONTINUE
40 CONTINUE
41 IF(13) 24,64,58
42 RETURN
43 END
FUNCTION G(N1,N)
  DIMENSION G(64)
  1 IF(N-6) 2,67,2
  2 IF (N-8) 3,5,3
  3 IF (N-13) 4,10,4
  4 IF (N-16) 5,16,5
  5 IF (N-32) 6,47,23152
  6 G(1)=.3226617647*23152
  7 G(2)=.23038846265
  8 G(3)=.2385191888197
  9 IF (1-3) 61,61,62
  10 G(1)=G(1)
  11 GO TO 7
  12 *N7-1
  13 *N7-1
  14 GO TO 7
  15 G(1)=.963269356497536
  16 G(2)=.796666477613627
  17 G(3)=.52552489161329
  18 G(4)=.13343646495656
  19 IF (1-4) 3,4,5
  20 G(1)=G(1)
  21 GO TO 7
  22 *N7-1
  23 G(1)=.9730628517172
  24 G(2)=.8650336666895
  25 G(3)=.6794969299024
  26 G(4)=.5339539412347
  27 G(5)=.14687433081631
  28 IF (1-5) 11,11,12
  29 G(1)=G(1)
  30 GO TO 7
  31 *N11-1
  32 G(1)=.9730628517172
  33 G(2)=.8650336666895
  34 G(3)=.6794969299024
  35 G(4)=.5339539412347
  36 G(5)=.14687433081631
  37 IF (1-5) 11,11,12
  38 G(1)=G(1)
  39 GO TO 7
  40 *N11-1
  41 G(1)=.9730628517172
  42 G(2)=.8650336666895
  43 G(3)=.6794969299024
  44 G(4)=.5339539412347
  45 G(5)=.14687433081631
  46 IF (1-5) 11,11,12
  47 G(1)=G(1)
  48 GO TO 7
  49 *N11-1
  50 G(1)=.9730628517172
  51 G(2)=.8650336666895
  52 G(3)=.6794969299024
  53 G(4)=.5339539412347
  54 G(5)=.14687433081631
  55 IF (1-5) 11,11,12
  56 G(1)=G(1)
  57 GO TO 7
  58 *N11-1
  59 G(1)=.9730628517172
  60 G(2)=.8650336666895
  61 G(3)=.6794969299024
  62 G(4)=.5339539412347
  63 G(5)=.14687433081631
  64 IF (1-5) 11,11,12
  65 G(1)=G(1)
  66 GO TO 7
  67 *N11-1
  68 G(1)=.9730628517172
  69 G(2)=.8650336666895
  70 G(3)=.6794969299024
  71 G(4)=.5339539412347
  72 G(5)=.14687433081631
  73 IF (1-5) 11,11,12
  74 G(1)=G(1)
  75 GO TO 7
  76 *N11-1
  77 G(1)=.9730628517172
  78 G(2)=.8650336666895
  79 G(3)=.6794969299024
  80 G(4)=.5339539412347
  81 G(5)=.14687433081631
  82 IF (1-5) 11,11,12
  83 G(1)=G(1)
  84 GO TO 7
  85 *N11-1
  86 G(1)=.9730628517172
  87 G(2)=.8650336666895
  88 G(3)=.6794969299024
  89 G(4)=.5339539412347
  90 G(5)=.14687433081631
  91 IF (1-5) 11,11,12
  92 G(1)=G(1)
  93 GO TO 7
  94 *N11-1
  95 G(1)=.9730628517172
  96 G(2)=.8650336666895
  97 G(3)=.6794969299024
  98 G(4)=.5339539412347
  99 G(5)=.14687433081631
  100 IF (1-5) 11,11,12
  101 G(1)=G(1)
  102 GO TO 7
  103 *N11-1
  104 G(1)=.9730628517172
  105 G(2)=.8650336666895
  106 G(3)=.6794969299024
  107 G(4)=.5339539412347
  108 G(5)=.14687433081631
  109 IF (1-5) 11,11,12
  110 G(1)=G(1)
  111 GO TO 7
  112 *N11-1
  113 G(1)=.9730628517172
  114 G(2)=.8650336666895
  115 G(3)=.6794969299024
  116 G(4)=.5339539412347
  117 G(5)=.14687433081631
  118 IF (1-5) 11,11,12
  119 G(1)=G(1)
  120 GO TO 7
  121 *N11-1
  122 G(1)=.9730628517172
  123 G(2)=.8650336666895
  124 G(3)=.6794969299024
  125 G(4)=.5339539412347
  126 G(5)=.14687433081631
  127 IF (1-5) 11,11,12
  128 G(1)=G(1)
  129 GO TO 7
  130 *N11-1
  131 G(1)=.9730628517172
  132 G(2)=.8650336666895
  133 G(3)=.6794969299024
  134 G(4)=.5339539412347
  135 G(5)=.14687433081631
  136 IF (1-5) 11,11,12
  137 G(1)=G(1)
  138 GO TO 7
  139 *N11-1
  140 G(1)=.9730628517172
  141 G(2)=.8650336666895
  142 G(3)=.6794969299024
  143 G(4)=.5339539412347
  144 G(5)=.14687433081631
  145 IF (1-5) 11,11,12
  146 G(1)=G(1)
  147 GO TO 7
  148 *N11-1
  149 G(1)=.9730628517172
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  151 G(3)=.6794969299024
  152 G(4)=.5339539412347
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  154 IF (1-5) 11,11,12
  155 G(1)=G(1)
  156 GO TO 7
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  162 G(5)=.14687433081631
  163 IF (1-5) 11,11,12
  164 G(1)=G(1)
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  167 G(1)=.9730628517172
  168 G(2)=.8650336666895
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  170 G(4)=.5339539412347
  171 G(5)=.14687433081631
  172 IF (1-5) 11,11,12
  173 G(1)=G(1)
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  199 IF (1-5) 11,11,12
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  202 *N11-1
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  205 G(3)=.6794969299024
  206 G(4)=.5339539412347
  207 G(5)=.14687433081631
  208 IF (1-5) 11,11,12
  209 G(1)=G(1)
  210 GO TO 7
  211 *N11-1
  212 G(1)=.9730628517172
  213 G(2)=.8650336666895
  214 G(3)=.6794969299024
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  217 IF (1-5) 11,11,12
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  222 G(2)=.8650336666895
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  225 G(5)=.14687433081631
  226 IF (1-5) 11,11,12
  227 G(1)=G(1)
  228 GO TO 7
  229 *N11-1
  230 G(1)=.9730628517172
  231 G(2)=.8650336666895
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  249 G(2)=.8650336666895
  250 G(3)=.6794969299024
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  252 G(5)=.14687433081631
  253 IF (1-5) 11,11,12
  254 G(1)=G(1)
  255 GO TO 7
  256 *N11-1
  257 G(1)=.9730628517172
  258 G(2)=.8650336666895
  259 G(3)=.6794969299024
  260 G(4)=.5339539412347
  261 G(5)=.14687433081631
  262 IF (1-5) 11,11,12
  263 G(1)=G(1)
  264 GO TO 7
  265 *N11-1
  266 G(1)=.9730628517172
  267 G(2)=.8650336666895
  268 G(3)=.6794969299024
  269 G(4)=.5339539412347
  270 G(5)=.14687433081631
  271 IF (1-5) 11,11,12
  272 G(1)=G(1)
  273 GO TO 7
  274 *N11-1
  275 G(1)=.9730628517172
  276 G(2)=.8650336666895
  277 G(3)=.6794969299024
  278 G(4)=.5339539412347
  279 G(5)=.14687433081631
  280 IF (1-5) 11,11,12
  281 G(1)=G(1)
  282 GO TO 7
  283 *N11-1
  284 G(1)=.9730628517172
  285 G(2)=.8650336666895
  286 G(3)=.6794969299024
  287 G(4)=.5339539412347
  288 G(5)=.14687433081631
  289 IF (1-5) 11,11,12
  290 G(1)=G(1)
  291 GO TO 7
  292 *N11-1
  293 G(1)=.9730628517172
  294 G(2)=.8650336666895
  295 G(3)=.6794969299024
  296 G(4)=.5339539412347
  297 G(5)=.14687433081631
  298 IF (1-5) 11,11,12
  299 G(1)=G(1)
  300 GO TO 7
  301 *N11-1
  302 G(1)=.9730628517172
  303 G(2)=.8650336666895
  304 G(3)=.6794969299024
  305 G(4)=.5339539412347
  306 G(5)=.14687433081631
  307 IF (1-5) 11,11,12
  308 G(1)=G(1)
  309 GO TO 7
  310 *N11-1
  311 G(1)=.9730628517172
  312 G(2)=.8650336666895
  313 G(3)=.6794969299024
  314 G(4)=.5339539412347
  315 G(5)=.14687433081631
  316 IF (1-5) 11,11,12
  317 G(1)=G(1)
  318 GO TO 7
  319 *N11-1
  320 G(1)=.9730628517172
  321 G(2)=.8650336666895
  322 G(3)=.6794969299024
  323 G(4)=.5339539412347
  324 G(5)=.14687433081631
  325 IF (1-5) 11,11,12
  326 G(1)=G(1)
  327 GO TO 7
  328 *N11-1
  329 G(1)=.9730628517172
  330 G(2)=.8650336666895
  331 G(3)=.6794969299024
  332 G(4)=.5339539412347
  333 G(5)=.14687433081631
  334 IF (1-5) 11,11,12
  335 G(1)=G(1)
  336 GO TO 7
  337 *N11-1
  338 G(1)=.9730628517172
  339 G(2)=.8650336666895
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  342 G(5)=.14687433081631
  343 IF (1-5) 11,11,12
  344 G(1)=G(1)
  345 GO TO 7
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  349 G(3)=.6794969299024
  350 G(4)=.5339539412347
  351 G(5)=.14687433081631
  352 IF (1-5) 11,11,12
  353 G(1)=G(1)
  354 GO TO 7
  355 *N11-1
  356 G(1)=.9730628517172
  357 G(2)=.8650336666895
  358 G(3)=.6794969299024
  359 G(4)=.5339539412347
  360 G(5)=.14687433081631
  361 IF (1-5) 11,11,12
  362 G(1)=G(1)
  363 GO TO 7
  364 *N11-1
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  366 G(2)=.8650336666895
  367 G(3)=.6794969299024
  368 G(4)=.5339539412347
  369 G(5)=.14687433081631
  370 IF (1-5) 11,11,12
  371 G(1)=G(1)
  372 GO TO 7
  373 *N11-1
  374 G(1)=.9730628517172
  375 G(2)=.8650336666895
  376 G(3)=.6794969299024
  377 G(4)=.5339539412347
  378 G(5)=.14687433081631
  379 IF (1-5) 11,11,12
  380 G(1)=G(1)
  381 GO TO 7
  382 *N11-1
  383 G(1)=.9730628517172
  384 G(2)=.8650336666895
  385 G(3)=.6794969299024
  386 G(4)=.5339539412347
  387 G(5)=.14687433081631
  388 IF (1-5) 11,11,12
  389 G(1)=G(1)
  390 GO TO 7
  391 *N11-1
  392 G(1)=.9730628517172
  393 G(2)=.8650336666895
  394 G(3)=.6794969299024
  395 G(4)=.5339539412347
  396 G(5)=.14687433081631
  397 IF (1-5) 11,11,12
  398 G(1)=G(1)
  399 GO TO 7
  400 *N11-1
  401 G(1)=.9730628517172
  402 G(2)=.8650336666895
  403 G(3)=.6794969299024
  404 G(4)=.5339539412347
  405 G(5)=.14687433081631
  406 IF (1-5) 11,11,12
  407 G(1)=G(1)
  408 GO TO 7
  409 *N11-1
  410 G(1)=.9730628517172
  411 G(2)=.8650336666895
  412 G(3)=.6794969299024
  413 G(4)=.5339539412347
  414 G(5)=.14687433081631
  415 IF (1-5) 11,11,12
  416 G(1)=G(1)
  417 GO TO 7
  418 *N11-1
  419 G(1)=.9730628517172
  420 G(2)=.8650336666895
  421 G(3)=.6794969299024
  422 G(4)=.5339539412347
  423 G(5)=.14687433081631
  424 IF (1-5) 11,11,12
  425 G(1)=G(1)
  426 GO TO 7
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  428 G(1)=.9730628517172
  429 G(2)=.8650336666895
  430 G(3)=.6794969299024
  431 G(4)=.5339539412347
  432 G(5)=.14687433081631
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  440 G(4)=.5339539412347
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  459 G(5)=.14687433081631
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  475 G(3)=.6794969299024
  476 G(4)=.5339539412347
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  478 IF (1-5) 11,11,12
  479 G(1)=G(1)
  480 GO TO 7
  481 *N11-1
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  483 G(2)=.8650336666895
  484 G(3)=.6794969299024
  485 G(4)=.5339539412347
  486 G(5)=.14687433081631
  487 IF (1-5) 11,11,12
  488 G(1)=G(1)
  489 GO TO 7
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  491 G(1)=.9730628517172
  492 G(2)=.8650336666895
  493 G(3)=.6794969299024
  494 G(4)=.5339539412347
  495 G(5)=.14687433081631
  496 IF (1-5) 11,11,12
  497 G(1)=G(1)
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  501 G(2)=.8650336666895
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  520 G(3)=.6794969299024
  521 G(4)=.5339539412347
  522 G(5)=.14687433081631
  523 IF (1-5) 11,11,12
  524 G(1)=G(1)
  525 GO TO 7
  526 *N11-1
  527 G(1)=.9730628517172
  528 G(2)=.8650336666895
  529 G(3)=.6794969299024
  530 G(4)=.5339539412347
  531 G(5)=.14687433081631
  532 IF (1-5) 11,11,12
  533 G(1)=G(1)
  534 GO TO 7
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  536 G(1)=.9730628517172
  537 G(2)=.8650336666895
  538 G(3)=.6794969299024
  539 G(4)=.5339539412347
  540 G(5)=.14687433081631
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  542 G(1)=G(1)
  543 GO TO 7
  544 *N11-1
  545 G(1)=.9730628517172
  546 G(2)=.8650336666895
  547 G(3)=.6794969299024
  548 G(4)=.5339539412347
  549 G(5)=.14687433081631
  550 IF (1-5) 11,11,12
  551 G(1)=G(1)
  552 GO TO 7
  553 *N11-1
  554 G(1)=.9730628517172
  555 G(2)=.8650336666895
  556 G(3)=.6794969299024
  557 G(4)=.5339539412347
  558 G(5)=.14687433081631
  559 IF (1-5) 11,11,12
  560 G(1)=G(1)
  561 GO TO 7
  562 *N11-1
  563 G(1)=.9730628517172
  564 G(2)=.8650336666895
  565 G(3)=.6794969299024
  566 G(4)=.5339539412347
  567 G(5)=.14687433081631
  568 IF (1-5) 11,11,12
  569 G(1)=G(1)
  570 GO TO 7
  571 *N11-1
  572 G(1)=.9730628517172
  573 G(2)=.8650336666895
  574 G(3)=.6794969299024
  575 G(4)=.5339539412347
  576 G(5)=.14687433081631
  577 IF (1-5) 11,11,12
  578 G(1)=G(1)
  579 GO TO 7
  580 *N11-1
  581 G(1)=.9730628517172
  582 G(2)=.8650336666895
  583 G(3)=.6794969299024
  584 G(4)=.5339539412347
  585 G(5)=.14687433081631
  586 IF (1-5) 11,11,12
  587 G(1)=G(1)
  588 GO TO 7
  589 *N11-1
  590 G(1)=.9730628517172
  591 G(2)=.8650336666895
  592 G(3)=.6794969299024
  593 G(4)=.5339539412347
  594 G(5)=.14687433081631
  595 IF (1-5) 11,11,12
  596 G(1)=G(1)
  597 GO TO 7
  598 *N11-1
  599 G(1)=.9730628517172
  600 G(2)=.8650336666895
  601 G(3)=.6794969299024
  602 G(4)=.5339539412347
  603 G(5)=.14687433081631
  604 IF (1-5) 11,11,12
  605 G(1)=G(1)
  606 GO TO 7
  607 *N11-1
  608 G(1)=.9730628517172
  609 G(2)=.8650336666895
  610 G(3)=.6794969299024
  611 G(4)=.5339539412347
  612 G(5)=.14687433081631
  613 IF (1-5) 11,11,12
  614 G(1)=G(1)
  615 GO TO 7
  616 *N11-1
  617 G(1)=.9730628517172
  
```


Program 2 Listing (continued)

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```

      SUBROUTINE STRUCT(N,S,Z,Y,PSI)
C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL
      COMMON /CNRA/ NNNN
      Y=5.0*S
      Z=0.0
      PSI=0.0
      RETURN
      END
      FUNCTION XLE(N,S)
C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL
      COMMON /CNRA/ NNNN
      XLE=-1.0
      RETURN
      END
      FUNCTION B(N,S)
C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL
      COMMON /CNRA/ NNNN
      B=1.0
      RETURN
      END
      SUBROUTINE FUNCTN(N,S,F)
C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL
      DIMENSION F(4)
      R=SQRT(1.0-S**2)
      F(1)=R
      F(2)=R*S**2
      F(3)=R*S**4
      F(4)=R*S**6
      RETURN
      END

```

Program 2 User-Coded Subprograms

| | | | | | | | | | | | |
|--|------|----|-----|---|----|---|---|----|----|---|-------|
| 1 | 1 | 1 | | | | | | | | | |
| C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL | | | | | | | | | | | |
| | 1.97 | | 0.0 | 1 | 16 | 3 | 3 | 10 | 10 | 0 | -0.38 |
| 10 | 10 | 10 | | | | | | | | | |
| | 5.0 | | | | | | | | | | |

| | | | |
|---|-----|-----|-----|
| 1 | .20 | .20 | .10 |
| 1 | .40 | .20 | .10 |
| 1 | .60 | .20 | .10 |
| 1 | .80 | .20 | .10 |
| 1 | .20 | .40 | .10 |
| 1 | .40 | .40 | .10 |
| 1 | .60 | .40 | .10 |
| 1 | .80 | .40 | .10 |
| 1 | .20 | .60 | .10 |
| 1 | .40 | .60 | .10 |
| 1 | .60 | .60 | .10 |
| 1 | .80 | .60 | .10 |
| 1 | .20 | .80 | .10 |
| 1 | .40 | .80 | .10 |
| 1 | .60 | .80 | .10 |
| 1 | .80 | .80 | .10 |

| | | | | | |
|---|-------|------|-------|------|-------|
| C SWRI RECTANGULAR HYDROFOIL, TORSIONAL MODE, RF=1.97 | | | | | |
| .176 | -.035 | .176 | .104 | .176 | .243 |
| .176 | .381 | .363 | -.072 | .363 | .215 |
| .363 | .501 | .363 | .787 | .559 | -.110 |
| .559 | .330 | .559 | .771 | .559 | 1.211 |
| .770 | -.152 | .770 | .455 | .770 | 1.062 |
| .770 | 1.669 | | | | |

Program 2 Punch Card Input


```

XCP=(SPMG/SLMG)*COS((SPPH-SLPH)*0.0174533)*(-1./XZ)+ARM      ANSL1340
YCP=(SPMG/SLMG)*COS((SPPH-SLPH)*0.0174533)*(+1./XZ)          ANSL1350
WRITE(6,214) XCP,YCP                                           ANSL1360
135 CONTINUE                                                    ANSL1370
DO 50 I=1,NCCP                                                  ANSL1380
  VR(I)=1.0+VR(I)                                              ANSL1390
50 CONTINUE                                                    ANSL1400
2 FORMAT(20H1CAMBER CASE NUMBER=IS,3H OF,IS,6H CASES)         ANSL1410
201 FORMAT(//23H CHECK INPUT PARAMETERS/4X,2HRF,8X,2HEM,7X,22HNS NCCP ANSL1420
1NOLT MOST NCP,3X,2HMP,3X,3HARM/ 2F10.5,6I5,F10.5 //7H SPAN= ANSL1430
2F10.5)                                                         ANSL1440
203 FORMAT(1HG,39X,4HREAL,11X,4HIMAG,11X,4H MAG,1GX,5HMPHASE/ ANSL1450
135H SECTION LIFT COEFFICIENT =,F10.6, 2F15.6,F15.2/ ANSL1460
235H SECTION PITCH MOM COEFF =,F10.6, 2F15.6,F15.2/ ANSL1470
335H SECTION ROLL MOM COEFF =,F10.6, 2F15.6,F15.2) ANSL1480
204 FORMAT(1H0,5X,3HPR MATRIX //(4E17.8)) ANSL1490
205 FORMAT(1H0,5X,9HPI MATRIX //(4E17.8)) ANSL1500
206 FORMAT(6F12.3) ANSL1510
208 FORMAT(1H0/(6F12.5)) ANSL1520
209 FORMAT(1H,32X,19HLOCAL COEFFICIENTS,10HANSL1530
10N SECTION,I2,23H AT SPANWISE POSITION S/// ANSL1540
246X,28HMENTS CALCULATED ABOUT X =,F6.2// ANSL1550
334X,5HMPHASE IS ANGLE BY WHICH QUANTITY LEADS DISPLACEMENT ANSL1560
210 FORMAT(1H0,2X,1HS,6X,3HCLR,7X,3HCLI,7X,4HCLMG,6X,4HCLPM,6X,4HCPMR,ANSL1570
16X,4HCPHI,6X,4HCPMG,6X,4HCPPI,6X,4HCRM,6X,4HCRMI,6X,4HCRMG,6X,4HCRMS,ANSL1580
2RPM /3X,1H=-) ANSL1590
3X,3H---,7X,3H---,7X,4H---,6X,4H---,6X,4H---,6X,4H---,6X,4H---,6X,4H---,ANSL1600
4,6X,4H---,6X,4H---,6X,4H---,6X,4H---,6X,4H---,6X,4H---) ANSL1610
211 FORMAT(1H,FS.2,3(F10.6,F9.2,1X)) ANSL1620
212 FORMAT(1H) ANSL1630
214 FORMAT(1H0,36HX-COORDINATE OF SECTION CP =,F10.6/ ANSL1640
135H SPANWISE COORDINATE OF SECTION CP=,F10.6) ANSL1650
215 FORMAT(///3X,1HS,5X, ANSL1660
2 4HF(1),5X,4HF(2),5X,4HF(3),5X,4HF(4),5X,4HF(5),5X,4HF(6) ANSL1670
3(6) / ANSL1680
4 3X,1H-, 5X,4H--- ANSL1690
5,5X,4H---,5X,4H---,5X,4H---,5X,4H---,5X,4H---) ANSL1700
216 FORMAT(1H,FS.2,1P6E9.1) ANSL1710
219 FORMAT(1H,8H SF(1)= 10F10.5) ANSL1720
220 FORMAT(1H,8H NI(2)= 20I5) ANSL1730
230 FORMAT(1H,1P5E12.3) ANSL1740
231 FORMAT(1H,///50H XEAL COEFFICIENT MATRIX CR (SPANWISE X CHORDWISE) ANSL1750
1) ANSL1760
241 FORMAT(1H,///50H IMAG COEFFICIENT MATRIX CI (SPANWISE X CHORDWISE) ANSL1770
1) ANSL1780
900 FORMAT(1H0,20A4) ANSL1790
923 FORMAT(2F10.5,6I5,F10.5,I5,F10.5) ANSL1800
924 FORMAT(4E17.8) ANSL1810
925 FORMAT(6F10.5) ANSL1820
926 FORMAT(14I5) ANSL1830
ENG ANSL1840

```

Program 3 Listing (continued)

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```

      FUNCTION XLE(N,S)
C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL--RF=1.97
      XLE=-1.0
      RETURN
      END
      FUNCTION R(N,S)
C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL--RF=1.97
      R=1.0
      RETURN
      END
      SUBROUTINE FUNCTN(N,S,F)
C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL--RF=1.97
      DIMENSION F(6)
      R=SQRT(1.0-S**2)
      F(1)=R
      F(2)=R*S**2
      F(3)=R*S**4
      F(4)=R*S**6
      RETURN
      END

```

Program 3 User-Coded Subprograms

C UNSTEADY LOADING TEST CASE--SWRI RECTANGULAR HYDROFOIL

J3=0 INFINITE FLUID

1.97000 5.00000 1 3 3 16 10 10 0.00000 1 -.38

1.00000

10 10 10

| | | | |
|----------------|----------------|----------------|----------------|
| .18477725E-01 | -.30675943E-01 | -.11228947E+00 | -.10071209E+00 |
| .17351283E+00 | .63868057E+00 | .11804733E+00 | -.20441520E+00 |
| -.75227897E+00 | -.10196953E-02 | -.57613615E-02 | .10391180E+00 |
| .96467961E-02 | .24478672E-01 | -.57761464E+00 | -.12011244E-01 |
| -.27941997E-01 | .68135495E+00 | -.45963889E-02 | .81337399E-02 |
| .10753080E+00 | .28900852E-01 | -.47214427E-01 | -.60335955E+00 |
| -.34580948E-01 | .55652244E-01 | .71269003E+00 | .39861609E-02 |
| .22146141E-01 | -.10554828E+00 | -.19942488E-01 | -.10016424E+00 |
| .58583096E+00 | .23218220E-01 | .11458083E+00 | -.69026990E+00 |
| .33613705E-02 | -.49875540E-02 | -.17444346E-01 | .39689233E-01 |
| -.70764595E-01 | -.26689322E+00 | -.77143908E-01 | .13569095E+00 |
| .50662731E+00 | .25138325E-03 | -.16810617E-02 | .17340131E-01 |
| -.59951081E-02 | -.67279098E-02 | .23824915E+00 | .10129240E-01 |
| .15924178E-01 | -.45886014E+00 | -.40216593E-03 | .12120437E-02 |
| .17135733E-01 | -.13556733E-01 | .19814147E-01 | .25341759E+00 |
| .24899114E-01 | -.37279304E-01 | -.48520604E+00 | .83796944E-03 |
| .60652896E-02 | -.17639624E-01 | .78610360E-02 | .30108880E-01 |
| -.24092325E+00 | -.15626980E-01 | -.66090388E-01 | .46380663E+00 |
| -.68822785E-02 | .12109707E-01 | .44706184E-01 | .11026120E+00 |
| -.19092192E+00 | -.70222948E+00 | -.15152783E+00 | .26216933E+00 |
| .96111445E+00 | .70063470E-03 | .14143330E-02 | -.38674223E-01 |
| -.96925924E-02 | -.26115529E-01 | .61912887E+00 | .12673153E-01 |
| .36828909E-01 | -.84867990E+00 | .21459717E-02 | -.35967466E-02 |
| -.41516355E-01 | -.32307280E-01 | .54825850E-01 | .65690008E+00 |
| .44169827E-01 | -.75778312E-01 | -.90181716E+00 | -.11989277E-02 |
| -.59804207E-02 | .39810856E-01 | .20269119E-01 | .10679774E+00 |
| -.63497004E+00 | -.27752678E-01 | -.14874322E+00 | .87267536E+00 |
| .24731548E-02 | -.41605870E-02 | -.16094111E-01 | -.43653185E-01 |
| .79513627E-01 | .30205130E+00 | .12571859E+00 | -.22177948E+00 |
| -.82448680E+00 | -.22543916E-03 | -.39252748E-03 | .13865961E-01 |
| .72596514E-02 | .26710346E-02 | -.25361066E+00 | -.15304997E-01 |
| -.21226610E-01 | .72172119E+00 | -.65190029E-03 | .11991497E-02 |
| .14168333E-01 | .14956353E-01 | -.23406082E-01 | -.26544781E+00 |
| -.38529186E-01 | .62523197E-01 | .75238118E+00 | .44277223E-03 |
| .25476870E-02 | -.13568881E-01 | -.62931141E-02 | -.27661187E-01 |
| .25196399E+00 | .21605686E-01 | .10733603E+00 | -.72575881E+00 |
| .27842759E-02 | .58649089E-02 | .63458329E-01 | -.16845116E-01 |

Program 3 Punch Card Input

| | | | |
|----------------|----------------|----------------|----------------|
| -.22563782E-01 | -.34785077E+00 | .19965080E-01 | .24793980E-01 |
| .40945601E+00 | -.13649903E-02 | .23900082E-01 | -.42646661E-02 |
| .87299895E-02 | -.11604061E+00 | .18108455E-01 | -.10594658E-01 |
| .13404100E+00 | -.18825516E-01 | -.52204462E-02 | .25314149E-01 |
| .87475295E-02 | .29726270E-01 | -.12833876E+00 | -.59411380E-01 |
| -.35386527E-01 | .14899775E+00 | .75389699E-01 | .29767810E-02 |
| .55270247E-02 | -.63546648E-01 | -.20345209E-01 | -.19035698E-01 |
| .34653487E+00 | .24068757E-01 | .20118828E-01 | -.39933747E+00 |
| .35767808E-03 | .21384147E-02 | .11133602E-01 | .72088548E-02 |
| .33884298E-02 | .14011575E+00 | -.13517753E-01 | -.10458343E-01 |
| -.27181776E+00 | -.86959528E-04 | .58314003E-02 | -.20342107E-02 |
| -.44586890E-02 | .38866654E-01 | .27467066E-02 | .81089504E-02 |
| -.81037100E-01 | -.50173060E-03 | -.71530756E-03 | .56772580E-02 |
| -.10841301E-02 | -.13522064E-01 | .45507849E-01 | .45399362E-01 |
| .25458087E-01 | -.92297972E-01 | -.78216640E-01 | .29677536E-03 |
| .23677670E-02 | -.13818183E-01 | .80872811E-02 | .38955707E-03 |
| -.11124130E+00 | -.14968275E-01 | -.54109258E-02 | .22329982E+00 |
| -.12511891E-02 | -.12947438E-02 | -.23170867E-01 | .19056987E-01 |
| .25012401E-01 | .37349280E+00 | -.26126349E-01 | -.35489401E-01 |
| -.51350157E+00 | .58241137E-03 | -.74191113E-02 | .15848975E-02 |
| -.89090294E-02 | .12583551E+00 | -.26731414E-01 | .12158099E-01 |
| -.17462386E+00 | .37513179E-01 | .19436527E-02 | -.85413046E-02 |
| -.19626800E-02 | -.30909584E-01 | .14087106E+00 | .34797660E-01 |
| .42205847E-01 | -.19512794E+00 | -.41532819E-01 | -.17780829E-02 |
| -.10760498E-02 | .27420033E-01 | .25627722E-01 | .21748995E-01 |
| -.42659756E+00 | -.35513202E-01 | -.31330309E-01 | .59336940E+00 |
| .39935926E-03 | .57127361E-03 | .81346054E-02 | -.86116472E-02 |
| -.26830213E-02 | -.14690516E+00 | .22635650E-01 | .20833747E-01 |
| .42838977E+00 | -.18732584E-03 | .28652938E-02 | -.73796541E-03 |
| .43514301E-02 | -.38912777E-01 | .99195763E-02 | -.11300588E-01 |
| .13227360E+00 | -.29624449E-01 | -.68598156E-03 | .31465266E-02 |
| .11791485E-02 | .12888224E-01 | -.47843419E-01 | -.24397777E-01 |
| -.36321571E-01 | .15188219E+00 | .61592235E-01 | .43786899E-03 |
| .47716782E-03 | -.94499020E-02 | -.12378642E-01 | .13914201E-03 |
| .17250962E+00 | .30493266E-01 | .15464593E-01 | -.47494711E+00 |

C SWRI RECTANGULAR HYDROFOIL, TORSIONAL MODE, RF=1.97

| | | | | | |
|------|-------|------|-------|------|-------|
| .176 | -.035 | .176 | .104 | .176 | .243 |
| .176 | .381 | .363 | -.072 | .363 | .215 |
| .363 | .501 | .363 | .787 | .559 | -.110 |
| .559 | .330 | .559 | .771 | .559 | 1.211 |
| .770 | -.152 | .770 | .455 | .770 | 1.062 |
| .770 | 1.669 | | | | |

Program 3 Punch Card Input (continued)

APPENDIX D
PROGRAM 1 OUTPUT FOR SAMPLE CALCULATION

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NUMBER OF FOIL CONFIGURATIONS= 1

FOIL CONFIGURATION NUMBER 1

C HYSTAD INVERTED T-FOIL STEADY LOADING TEST CASE--PROGRAM CHECK ONLY

CHECK INPUT PARAMETERS

| RF | EM | NS | HQCP | HOLT | MOST | HCP | HP | J3 | ARM |
|---------|---------|---------|---------|------|------|-----|----|----|----------|
| 0.00000 | 0.00000 | 3 | 40 | 3 | 2 | 10 | 10 | 1 | -0.00000 |
| NI(2)= | 10 | 0 | 10 | 0 | 10 | 0 | 10 | | |
| AF(1)= | 1.94950 | 1.94950 | 4.65100 | | | | | | |

| CONTROL POINT NO. | SECTION | NO. | ETA | SOS |
|-------------------|---------|-----|------|------|
| 1 | 1 | 13 | .978 | .940 |
| 1 | 1 | 14 | .978 | .766 |
| 1 | 1 | 15 | .978 | .500 |
| 1 | 1 | 16 | .978 | .173 |
| 1 | 1 | 17 | .978 | .060 |
| 1 | 1 | 18 | .978 | .100 |
| 1 | 1 | 19 | .978 | .100 |
| 1 | 1 | 20 | .978 | .100 |
| 1 | 1 | 21 | .978 | .100 |
| 1 | 1 | 22 | .978 | .100 |
| 1 | 1 | 23 | .978 | .100 |
| 1 | 1 | 24 | .978 | .100 |
| 1 | 1 | 25 | .978 | .100 |
| 1 | 1 | 26 | .978 | .100 |
| 1 | 1 | 27 | .978 | .100 |
| 1 | 1 | 28 | .978 | .100 |
| 1 | 1 | 29 | .978 | .100 |

Program 1 Output -- Steady Loading Test Case

| | | | |
|----------------|----------------|----------------|----------------|
| .17268889E-01 | .17008615E-03 | .38653098E-03 | .16814701E-02 |
| .23580888E-02 | .58966085E-02 | .30451252E-01 | .22168055E-03 |
| .60150682E-03 | .30423147E-02 | .22608198E-02 | .61576884E-02 |
| .44852964E-01 | .20117711E-03 | .61663425E-03 | .45012645E-02 |
| .05372044E-03 | .12472506E-02 | -.58401629E-02 | .13892207E-03 |
| .20296194E-03 | -.71475775E-03 | .23753490E-02 | .36435178E-02 |
| -.18986243E-01 | .25518000E-03 | .40504958E-03 | -.19602326E-02 |
| .37992453E-02 | .60346421E-02 | -.34421278E-01 | .36949784E-03 |
| .61582892E-03 | -.34510200E-02 | .41844288E-02 | .66737288E-02 |
| -.40704336E-01 | .39635862E-03 | .66626746E-03 | -.40553000E-02 |

CAMBER CASE NUMBER= 1 OF 1 CASES

C MYSTAD FOIL AT 4 DEG. INCIDENCE

| | | |
|---------|---------|---------|
| .02200 | .02200 | .02200 |
| .02200 | .06200 | .06200 |
| .06200 | .06200 | .09600 |
| .09600 | .09600 | .09600 |
| .15300 | .15300 | .15300 |
| .15300 | .02200 | .02200 |
| .02200 | .02200 | .06200 |
| .06200 | .06200 | .06200 |
| .09600 | .09600 | .09600 |
| .09600 | .15300 | .15300 |
| .15300 | .15300 | 0.00000 |
| 0.00000 | 0.00000 | 0.00000 |
| 0.00000 | 0.00000 | 0.00000 |
| 0.00000 | 0.00000 | 0.00000 |
| 0.00000 | 0.00000 | 0.00000 |
| 0.00000 | 0.00000 | 0.00000 |

REAL COEFFICIENT MATRIX CR (SPANWISE X CHORDWISE)

| | | |
|------------|-----------|------------|
| -1.761E-05 | 1.732E-07 | -2.140E-06 |
| 1.210E-02 | 1.213E-02 | -1.994E-02 |

LOCAL COEFFICIENTS AND SPANWISE FUNCTION VALUES ON SECTION 1 AT SPANWISE POSITION S
MOMENTS CALCULATED ABOUT X = -0.060

| S | CLR | CPMR | CMR | F(1) | F(2) | F(3) | F(4) |
|------|---------|----------|----------|----------|---------|------|------|
| 0.00 | .306782 | .040600 | 0.000000 | -5.0E-02 | 5.0E-02 | ---- | ---- |
| .05 | .306398 | .031326 | .014933 | -5.0E-02 | 5.0E-02 | | |
| .10 | .305244 | .022021 | .029754 | -5.0E-02 | 5.0E-02 | | |
| .15 | .303311 | .012752 | .044348 | -4.9E-02 | 4.9E-02 | | |
| .20 | .300584 | .003589 | .058599 | -4.9E-02 | 4.9E-02 | | |
| .25 | .297040 | -.005394 | .072385 | -4.8E-02 | 4.8E-02 | | |
| .30 | .292651 | -.014123 | .085579 | -4.8E-02 | 4.8E-02 | | |
| .35 | .287378 | -.022518 | .098043 | -4.7E-02 | 4.7E-02 | | |
| .40 | .281170 | -.030495 | .109620 | -4.6E-02 | 4.6E-02 | | |
| .45 | .273965 | -.037960 | .120171 | -4.5E-02 | 4.5E-02 | | |
| .50 | .265681 | -.044889 | .129486 | -4.3E-02 | 4.3E-02 | | |
| .55 | .256213 | -.050824 | .137359 | -4.2E-02 | 4.2E-02 | | |
| .60 | .245425 | -.056167 | .143537 | -4.0E-02 | 4.0E-02 | | |
| .65 | .233134 | -.060372 | .147711 | -3.8E-02 | 3.8E-02 | | |
| .70 | .219886 | -.063328 | .149488 | -3.6E-02 | 3.6E-02 | | |
| .75 | .202917 | -.064762 | .148345 | -3.3E-02 | 3.3E-02 | | |
| .80 | .184069 | -.064287 | .143537 | -3.0E-02 | 3.0E-02 | | |
| .85 | .161687 | -.061387 | .133898 | -2.6E-02 | 2.6E-02 | | |
| .90 | .133723 | -.054754 | .117312 | -2.2E-02 | 2.2E-02 | | |
| .95 | .095793 | -.042186 | .088705 | -1.6E-02 | 1.6E-02 | | |
| 1.00 | .000000 | -.000000 | .000000 | -1.3E-08 | 1.3E-08 | | |

SECTION LIFT COEFFICIENT = .240933
SECTION PITCH MOM COEFF = -.029668
SECTION ROLL MOM COEFF = .099666
X-COORDINATE OF SECTION CP = .246274
SPANWISE COORDINATE OF SECTION CP = .027335

Program 1 Output -- Steady Loading Test Case (continued)

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LOCAL COEFFICIENTS AND SPANWISE FUNCTION VALUES ON SECTION 2 AT SPANWISE POSITION S
MOMENTS CALCULATED ABOUT X = 0.000

| S | CLR | CPMR | CRMR | F(1) | F(2) | F(3) | F(4) |
|------|---------|----------|----------|---------|---------|------|------|
| ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 0.00 | .306250 | .000464 | 0.000000 | 4.0E-02 | 5.0E-02 | | |
| .05 | .305066 | .031209 | .014907 | 4.0E-02 | 5.0E-02 | | |
| .10 | .304714 | .021922 | .029702 | 4.0E-02 | 5.0E-02 | | |
| .15 | .302705 | .012672 | .044271 | 4.0E-02 | 4.9E-02 | | |
| .20 | .300062 | .003528 | .050497 | 3.9E-02 | 4.9E-02 | | |
| .25 | .296525 | -.005437 | .072259 | 3.9E-02 | 4.8E-02 | | |
| .30 | .292143 | -.014148 | .085430 | 3.8E-02 | 4.8E-02 | | |
| .35 | .286079 | -.022526 | .097872 | 3.7E-02 | 4.7E-02 | | |
| .40 | .280082 | -.030486 | .109438 | 3.7E-02 | 4.6E-02 | | |
| .45 | .273490 | -.037934 | .119963 | 3.6E-02 | 4.5E-02 | | |
| .50 | .265220 | -.044768 | .129262 | 3.5E-02 | 4.3E-02 | | |
| .55 | .255769 | -.050870 | .137121 | 3.3E-02 | 4.2E-02 | | |
| .60 | .245000 | -.056100 | .143288 | 3.2E-02 | 4.0E-02 | | |
| .65 | .232729 | -.060294 | .147454 | 3.0E-02 | 3.8E-02 | | |
| .70 | .218706 | -.063242 | .149229 | 2.9E-02 | 3.6E-02 | | |
| .75 | .202565 | -.064671 | .148088 | 2.6E-02 | 3.3E-02 | | |
| .80 | .183750 | -.064193 | .143288 | 2.4E-02 | 3.0E-02 | | |
| .85 | .161327 | -.061215 | .133665 | 2.1E-02 | 2.6E-02 | | |
| .90 | .133491 | -.054669 | .117108 | 1.7E-02 | 2.2E-02 | | |
| .95 | .095626 | -.042040 | .088551 | 1.2E-02 | 1.6E-02 | | |
| 1.00 | .000000 | -.000000 | .000000 | 1.0E-08 | 1.3E-08 | | |

SECTION LIFT COEFFICIENT = .240515
SECTION PITCH MOM COEFF = -.029652
SECTION ROLL MOM COEFF = .059493

X-COORDINATE OF SECTION CP = .246574
SPANWISE COORDINATE OF SECTION CP = .827335

LOCAL COEFFICIENTS AND SPANWISE FUNCTION VALUES ON SECTION 3 AT SPANWISE POSITION S
MOMENTS CALCULATED ABOUT X = 3.000

| S | CLR | CPMR | CRMR | F(1) | F(2) | F(3) | F(4) |
|------|----------|---------|----------|---------|------|------|------|
| ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 0.00 | -.000369 | .000027 | 0.000000 | 9.0E-02 | 0. | | |
| .05 | -.000368 | .000027 | -.000330 | 9.0E-02 | 0. | | |
| .10 | -.000365 | .000027 | -.000059 | 8.9E-02 | 0. | | |
| .15 | -.000361 | .000027 | -.000087 | 8.8E-02 | 0. | | |
| .20 | -.000354 | .000026 | -.000114 | 8.6E-02 | 0. | | |
| .25 | -.000346 | .000026 | -.000140 | 8.4E-02 | 0. | | |
| .30 | -.000336 | .000025 | -.000163 | 8.2E-02 | 0. | | |
| .35 | -.000324 | .000024 | -.000182 | 7.9E-02 | 0. | | |
| .40 | -.000310 | .000023 | -.000200 | 7.6E-02 | 0. | | |
| .45 | -.000294 | .000022 | -.000214 | 7.2E-02 | 0. | | |
| .50 | -.000277 | .000020 | -.000222 | 6.7E-02 | 0. | | |
| .55 | -.000257 | .000019 | -.000228 | 6.3E-02 | 0. | | |
| .60 | -.000236 | .000017 | -.000229 | 5.8E-02 | 0. | | |
| .65 | -.000213 | .000016 | -.000223 | 5.2E-02 | 0. | | |
| .70 | -.000188 | .000014 | -.000211 | 4.6E-02 | 0. | | |
| .75 | -.000161 | .000012 | -.000195 | 3.9E-02 | 0. | | |
| .80 | -.000133 | .000010 | -.000171 | 3.2E-02 | 0. | | |
| .85 | -.000102 | .000008 | -.000140 | 2.5E-02 | 0. | | |
| .90 | -.000070 | .000005 | -.000102 | 1.7E-02 | 0. | | |
| .95 | -.000036 | .000003 | -.000055 | 8.8E-03 | 0. | | |
| 1.00 | -.000000 | .000000 | -.000000 | 5.8E-15 | 0. | | |

SECTION LIFT COEFFICIENT = -.000246
SECTION PITCH MOM COEFF = .000018
SECTION ROLL MOM COEFF = -.000149

X-COORDINATE OF SECTION CP = .213428
SPANWISE COORDINATE OF SECTION CP = 1.744125

Program 1 Output -- Steady Loading Test Case (continued)

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| PRESSURE COEFFICIENTS | | | | | PRESSURE COEFFICIENTS | | | | | PRESSURE COEFFICIENTS | | | | |
|-----------------------|-----------|------|------|------|-----------------------|-----------|------|------|------|-----------------------|------------|------|------|------|
| SECTION | SPAN | SOS | MOLT | MOST | SECTION | SPAN | SOS | MOLT | MOST | SECTION | SPAN | SOS | MOLT | MOST |
| 1 | 1.949 | 0.00 | 3 | 2 | 2 | 1.949 | 0.00 | 3 | 2 | 3 | 4.651 | 0.00 | 3 | 2 |
| XOC | CP | | | | XOC | CP | | | | XOC | CP | | | |
| .01 | .2944E+00 | | | | .01 | .2957E+00 | | | | .01 | -.1279E-02 | | | |
| .02 | .2895E+00 | | | | .02 | .2898E+00 | | | | .02 | -.9010E-03 | | | |
| .03 | .1711E+00 | | | | .03 | .1706E+00 | | | | .03 | -.7325E-03 | | | |
| .04 | .1482E+00 | | | | .04 | .1478E+00 | | | | .04 | -.6317E-03 | | | |
| .05 | .1327E+00 | | | | .05 | .1324E+00 | | | | .05 | -.5625E-03 | | | |
| .06 | .1214E+00 | | | | .06 | .1211E+00 | | | | .06 | -.5111E-03 | | | |
| .07 | .1124E+00 | | | | .07 | .1123E+00 | | | | .07 | -.4710E-03 | | | |
| .08 | .1056E+00 | | | | .08 | .1054E+00 | | | | .08 | -.4305E-03 | | | |
| .09 | .9991E-01 | | | | .09 | .9986E-01 | | | | .09 | -.4114E-03 | | | |
| .10 | .9514E-01 | | | | .10 | .9490E-01 | | | | .10 | -.3804E-03 | | | |
| .15 | .7966E-01 | | | | .15 | .7947E-01 | | | | .15 | -.3088E-03 | | | |
| .20 | .7140E-01 | | | | .20 | .7124E-01 | | | | .20 | -.2597E-03 | | | |
| .25 | .6656E-01 | | | | .25 | .6642E-01 | | | | .25 | -.2240E-03 | | | |
| .30 | .6361E-01 | | | | .30 | .6349E-01 | | | | .30 | -.1979E-03 | | | |
| .35 | .6179E-01 | | | | .35 | .6169E-01 | | | | .35 | -.1761E-03 | | | |
| .40 | .6007E-01 | | | | .40 | .6007E-01 | | | | .40 | -.1576E-03 | | | |
| .45 | .5994E-01 | | | | .45 | .5985E-01 | | | | .45 | -.1415E-03 | | | |
| .50 | .5939E-01 | | | | .50 | .5931E-01 | | | | .50 | -.1272E-03 | | | |
| .55 | .5883E-01 | | | | .55 | .5876E-01 | | | | .55 | -.1142E-03 | | | |
| .60 | .5812E-01 | | | | .60 | .5806E-01 | | | | .60 | -.1021E-03 | | | |
| .65 | .5710E-01 | | | | .65 | .5705E-01 | | | | .65 | -.9083E-04 | | | |
| .70 | .5561E-01 | | | | .70 | .5556E-01 | | | | .70 | -.8000E-04 | | | |
| .75 | .5344E-01 | | | | .75 | .5339E-01 | | | | .75 | -.6969E-04 | | | |
| .80 | .5033E-01 | | | | .80 | .5029E-01 | | | | .80 | -.5947E-04 | | | |
| .85 | .4589E-01 | | | | .85 | .4586E-01 | | | | .85 | -.4916E-04 | | | |
| .90 | .3944E-01 | | | | .90 | .3941E-01 | | | | .90 | -.3832E-04 | | | |
| .92 | .3600E-01 | | | | .92 | .3598E-01 | | | | .92 | -.3364E-04 | | | |
| .94 | .3181E-01 | | | | .94 | .3180E-01 | | | | .94 | -.2859E-04 | | | |
| .96 | .2651E-01 | | | | .96 | .2649E-01 | | | | .96 | -.2291E-04 | | | |
| .98 | .1912E-01 | | | | .98 | .1911E-01 | | | | .98 | -.1590E-04 | | | |
| 1.00 | .8423E-15 | | | | 1.00 | .8417E-15 | | | | 1.00 | -.1022E-17 | | | |

Program 1 Output -- Steady Loading Test Case (continued)

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APPENDIX E
PROGRAM 2 OUTPUT FOR SAMPLE CALCULATION

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| | | | |
|----------------|----------------|----------------|----------------|
| -.51350157E+00 | .50241137E-03 | -.74191113E-02 | .15040975E-02 |
| -.0790294E-02 | .12503551E+00 | -.26731414E-01 | .12150399E-01 |
| -.17462386E+00 | .37513179E-01 | .19436527E-02 | -.05413046E-02 |
| -.13626800E-02 | -.30909594E-01 | .14087106E+00 | .34797661E-01 |
| .42235847E-01 | -.19512794E+00 | -.41532819E-01 | -.17780829E-02 |
| -.13764490E-02 | .27420033E-01 | .25627722E-01 | .21740995E-01 |
| -.42659756E+00 | -.35513202E-01 | -.3133319E-01 | .59336940E+00 |
| .39935926E-03 | .57127361E-03 | .01346054E-02 | -.06116472E-02 |
| -.26433213E-02 | -.14690516E+00 | .22635653E-01 | .24833747E-01 |
| .42338977E+00 | -.10732544E-03 | .28652930E-02 | -.73796541E-03 |
| .43514321E-12 | -.30312777E-01 | .99195763E-02 | -.11304598E-01 |
| .13227360E+00 | -.29624449E-01 | -.68598156E-03 | .31465266E-02 |
| .11791495E-02 | .12688224E-01 | -.47043419E-01 | -.24397777E-01 |
| -.36321571E-01 | .15100219E+00 | .61592235E-01 | .43706099E-03 |
| .47716742E-03 | -.94499020E-02 | -.12370642E-01 | .13914201E-03 |
| .17250962E+00 | .30493266E-01 | .15464593E-01 | -.47494711E+00 |

CAMBER CASE NUMBER= 1 OF 1 CASES

C SMRI RECTANGULAR HYDROFOIL, TORSIONAL MODE, RF=1.97

| | | | | | |
|--------|---------|--------|---------|--------|---------|
| .17600 | -.03500 | .17600 | .13400 | .17600 | .24300 |
| .17600 | .30100 | .46300 | -.07200 | .36800 | .21500 |
| .36800 | .56100 | .30300 | .78700 | .55900 | -.11300 |
| .55900 | .33000 | .55900 | .77100 | .55900 | 1.21100 |
| .77100 | -.15200 | .77100 | .45500 | .77000 | 1.36200 |
| .77000 | 1.56900 | | | | |

REAL COEFFICIENT MATRIX CR (SPANWISE X CHORDWISE)

| | | |
|------------|------------|-----------|
| 4.090E-03 | -1.078E-02 | 1.855E-02 |
| 2.628E-12 | -3.547E-02 | 1.891E-01 |
| -3.373E-03 | 9.373E-05 | 3.353E-02 |

IMAG COEFFICIENT MATRIX CI (SPANWISE X CHORDWISE)

| | | |
|------------|------------|-----------|
| 1.703E-04 | 2.303E-02 | 1.751E-04 |
| -2.094E-03 | 1.743E-01 | 2.200E-03 |
| -4.983E-03 | -7.507E-03 | 0.056E-03 |

| S | F(1) | F(2) | F(3) | F(4) | F(5) | F(6) |
|------|---------|---------|---------|------|------|------|
| 0.00 | 1.0E+00 | 0. | 0. | | | |
| .05 | 1.0E+00 | 2.5E-03 | 6.2E-06 | | | |
| .10 | 9.9E-01 | 9.9E-03 | 9.9E-05 | | | |
| .15 | 9.9E-01 | 2.2E-02 | 5.7E-04 | | | |
| .20 | 9.8E-01 | 3.9E-02 | 1.6E-03 | | | |
| .25 | 9.7E-01 | 6.1E-02 | 3.4E-03 | | | |
| .30 | 9.5E-01 | 4.5E-02 | 7.7E-03 | | | |
| .35 | 9.4E-01 | 1.1E-01 | 1.4E-02 | | | |
| .40 | 9.2E-01 | 1.5E-01 | 2.3E-02 | | | |
| .45 | 8.9E-01 | 1.5E-01 | 3.7E-02 | | | |
| .50 | 8.7E-01 | 2.2E-01 | 5.4E-02 | | | |
| .55 | 8.4E-01 | 2.5E-01 | 7.6E-02 | | | |
| .60 | 8.1E-01 | 2.3E-01 | 1.0E-01 | | | |
| .65 | 7.6E-01 | 3.2E-01 | 1.4E-01 | | | |
| .70 | 7.1E-01 | 3.5E-01 | 1.7E-01 | | | |
| .75 | 6.6E-01 | 3.7E-01 | 2.1E-01 | | | |
| .80 | 6.0E-01 | 3.8E-01 | 2.5E-01 | | | |
| .85 | 5.3E-01 | 3.4E-01 | 2.7E-01 | | | |
| .90 | 4.4E-01 | 3.5E-01 | 2.9E-01 | | | |
| .95 | 3.1E-01 | 2.8E-01 | 2.5E-01 | | | |
| 1.00 | 2.5E-07 | 2.5E-07 | 2.5E-07 | | | |

Program 2 Output -- Steady Loading Test Case (continued)

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LOCAL COEFFICIENTS ON SECTION 1 AT SPANWISE POSITION S

MOMENTS CALCULATED ABOUT X = -.38

PHASE IS ANGLE BY WHICH QUANTITY LEADS DISPLACEMENT

| S | CLR | CLI | CLMG | CLPH | CPNR | CPMI | CPMG | CPPH | CRNR | CRMI | CRMG | CRPH |
|-----------------------------------|-----------|----------|----------|-------------|----------|-----------|----------|--------|-----------|-----------|-----------|--------|
| 0.00 | -.250886 | 2.307074 | 2.321332 | 96.35 | .365086 | -.428859 | .563212 | -49.59 | .000000 | 0.000000 | 0.000000 | 0.00 |
| .05 | -.267143 | 2.346108 | 2.361268 | 96.50 | .372773 | -.436512 | .574023 | -49.50 | -.033392 | .293263 | .295158 | 96.58 |
| .10 | -.297791 | 2.462412 | 2.488354 | 96.98 | .395721 | -.459332 | .606284 | -49.25 | -.074448 | .615603 | .621388 | 96.90 |
| .15 | -.348496 | 2.653590 | 2.676376 | 97.48 | .433584 | -.496895 | .659478 | -48.89 | -.134686 | .995096 | 1.603641 | 97.48 |
| .20 | -.418664 | 2.915618 | 2.945523 | 98.17 | .485781 | -.548492 | .732644 | -48.47 | -.209332 | 1.457809 | 1.472762 | 98.17 |
| .25 | -.507435 | 3.242811 | 3.282272 | 98.89 | .551474 | -.611113 | .824637 | -48.03 | -.317147 | 2.026756 | 2.051428 | 98.89 |
| .30 | -.613636 | 3.627753 | 3.679245 | 99.60 | .629534 | -.684333 | .933611 | -47.60 | -.460227 | 2.720815 | 2.759464 | 99.60 |
| .35 | -.735728 | 4.061211 | 4.127315 | 100.27 | .718543 | -.775785 | 1.057424 | -47.19 | -.643762 | 3.553559 | 3.611431 | 100.27 |
| .40 | -.871731 | 4.531997 | 4.615074 | 100.89 | .816710 | -.871130 | 1.193374 | -46.81 | -.871731 | 4.531997 | 4.615074 | 100.89 |
| .45 | -1.019121 | 5.026780 | 5.129047 | 101.46 | .921927 | -.972010 | 1.338164 | -46.46 | -1.146511 | 5.655127 | 5.770178 | 101.46 |
| .50 | -1.174697 | 5.529808 | 5.653202 | 101.99 | 1.031179 | -1.072477 | 1.487796 | -46.12 | -1.468372 | 6.912260 | 7.066532 | 101.99 |
| .55 | -1.334386 | 6.022500 | 6.168557 | 102.49 | 1.141424 | -1.173998 | 1.637412 | -45.81 | -1.834781 | 8.280937 | 8.481765 | 102.49 |
| .60 | -1.492974 | 6.482820 | 6.652512 | 102.97 | 1.249410 | -1.276316 | 1.781076 | -45.50 | -2.239461 | 9.724229 | 9.978769 | 102.97 |
| .65 | -1.643700 | 6.884297 | 7.077403 | 103.43 | 1.346916 | -1.350222 | 1.911419 | -45.20 | -2.671013 | 11.186983 | 11.501431 | 103.43 |
| .70 | -1.777633 | 7.194407 | 7.410767 | 103.88 | 1.433222 | -1.425200 | 2.019091 | -44.90 | -3.110858 | 12.590212 | 12.968842 | 103.88 |
| .75 | -1.882614 | 7.371787 | 7.608304 | 104.33 | 1.489390 | -1.468800 | 2.091807 | -44.60 | -3.529902 | 13.821958 | 14.265571 | 104.33 |
| .80 | -1.941338 | 7.361351 | 7.612067 | 104.78 | 1.511925 | -1.475463 | 2.112560 | -44.30 | -3.882677 | 14.720703 | 15.224134 | 104.78 |
| .85 | -1.927322 | 7.078143 | 7.335849 | 105.23 | 1.478933 | -1.427977 | 2.055811 | -44.00 | -4.095558 | 15.041053 | 15.588578 | 105.23 |
| .90 | -1.794635 | 6.384964 | 6.632381 | 105.70 | 1.357786 | -1.296832 | 1.877593 | -43.68 | -4.037929 | 14.366168 | 14.922857 | 105.70 |
| .95 | -1.448351 | 4.963880 | 5.164551 | 106.15 | 1.075810 | -1.015379 | 1.478730 | -43.37 | -3.420834 | 11.789025 | 12.275339 | 106.15 |
| 1.00 | -.000003 | .000010 | .000010 | 106.13 | .000002 | -.000002 | .000003 | -41.72 | -.000007 | .000024 | .000025 | 106.46 |
| REAL IMAG MAG PHASE | | | | | | | | | | | | |
| SECTION LIFT COEFFICIENT | | | | = -1.097349 | | 4.919882 | 5.040775 | 102.57 | | | | |
| SECTION PITCH MOM COEFF | | | | = .943126 | | -.964195 | 1.348762 | -45.63 | | | | |
| SECTION ROLL MOM COEFF | | | | = -1.749937 | | 7.152364 | 7.363327 | 103.75 | | | | |
| X-COORDINATE OF SECTION CP | | | | = .074845 | | | | | | | | |
| SPANWISE COORDINATE OF SECTION CP | | | | = 2.928892 | | | | | | | | |

Program 2 Output -- Unsteady Loading Test Case

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SEP 79 P K BESCH, E P ROOD

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3 OF 3

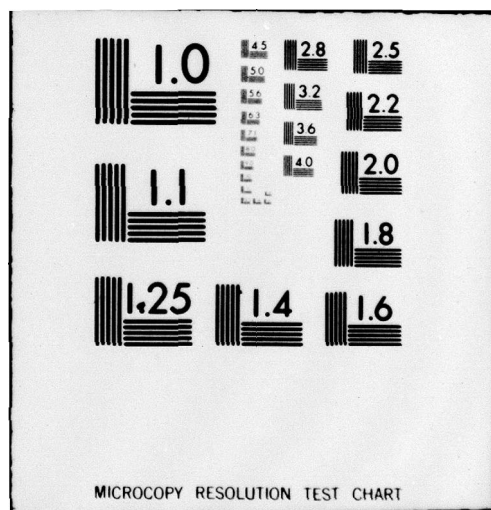
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APPENDIX F
PROGRAM 3 OUTPUT FOR SAMPLE CALCULATION

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